SAND2013-2169P

Wide-Bandgap Power Semiconductor Research at Sandia National Laboratories

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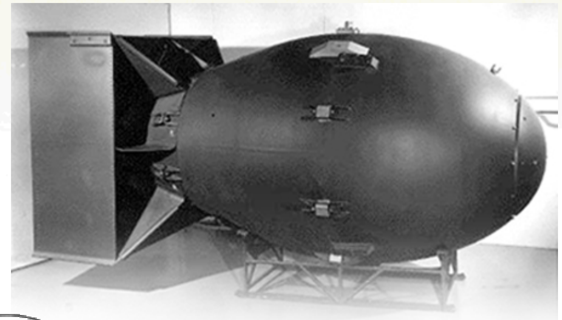
Presented at Auburn University Physics Department Colloquium

March 22, 2013

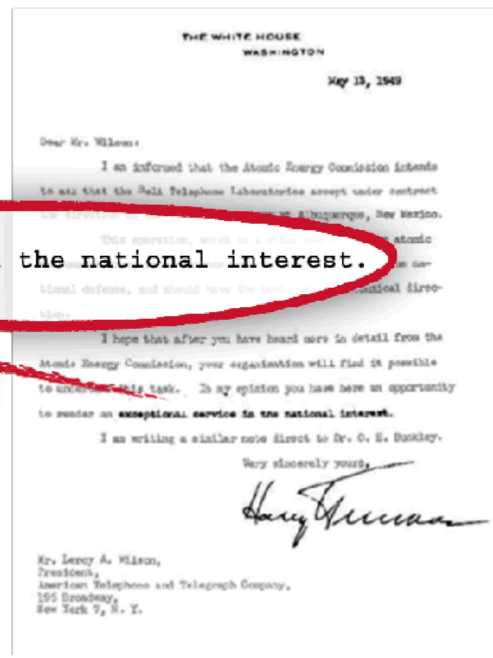
Parts of the work presented were supported by the DOE Office of Electricity, Energy Storage Program (Dr. Imre Gyuk) and GaN Initiative for Grid Applications (Dr. Mike Soboroff). Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Sandia National Laboratories

Sandia's History



exceptional service in the national interest.


THE WHITE HOUSE
WASHINGTON

May 13, 1949

Dear Mr. Wilson:

I am informed that the Atomic Energy Commission intends to ask that the Bell Telephone Laboratories accept under contract the direction of [illegible] at Albuquerque, New Mexico.

This operation, which is a vital [illegible] atomic [illegible] national defense, and should have the best [illegible] technical direction.

I hope that after you have heard more in detail from the Atomic Energy Commission, your organization will find it possible to undertake this task. In my opinion you have here an opportunity to render an **exceptional service in the national interest.**

I am writing a similar note direct to Dr. O. E. Buckley.

Very sincerely yours,

Harry Truman

Mr. Leroy A. Wilson,
President,
American Telephone and Telegraph Company,
195 Broadway,
New York 7, N. Y.

Sandia National Laboratories

Sandia's Governance Structure

Sandia Corporation

- AT&T: 1949–1993
- Martin Marietta: 1993–1995
- Lockheed Martin: 1995–present

Government owned, contractor operated

Federally funded research and development center

Sandia's Sites

Albuquerque,
New Mexico

Livermore,
California

Tonopah, Nevada

Waste Isolation Pilot Plant,
Carlsbad, New Mexico

Pantex, Texas

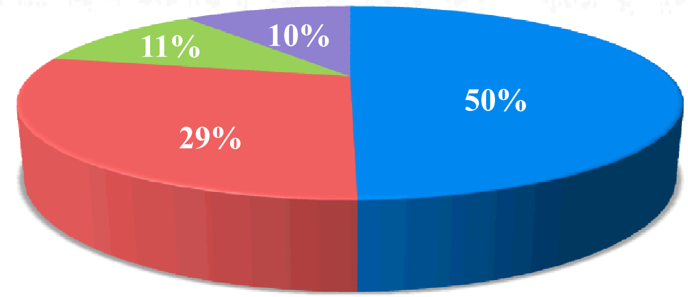
Kauai, Hawaii

Sandia
National
Laboratories

People and Budget

- On-site workforce: 10,605
- Regular employees: 8,859
- Gross payroll: ~$943 million

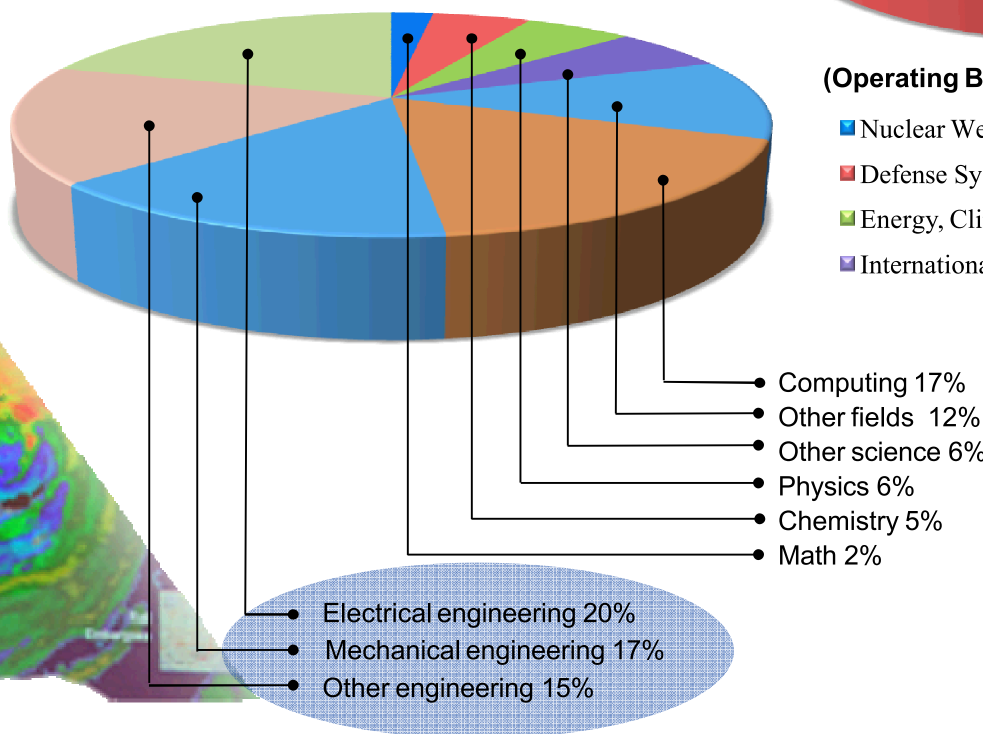
FY11 Operating Revenue
$2.4 billion

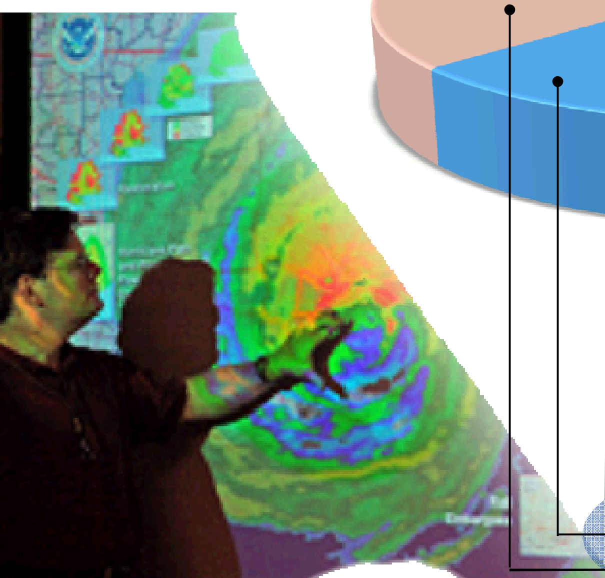


(Operating Budget)

- Nuclear Weapons
- Defense Systems & Assessments
- Energy, Climate & Infrastructure Security
- International, Homeland, and Nuclear Security

Technical staff (4,344) by discipline

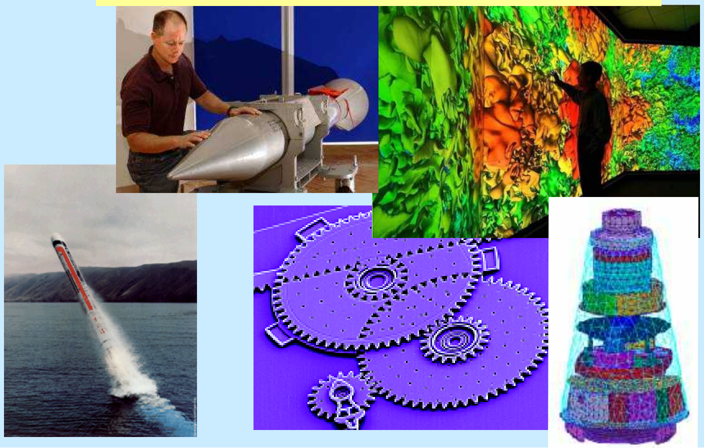




Sandia National Laboratories

Sandia's Four Application Mission Areas (SMUs)

Nuclear Weapons



Defense Systems & Assessments

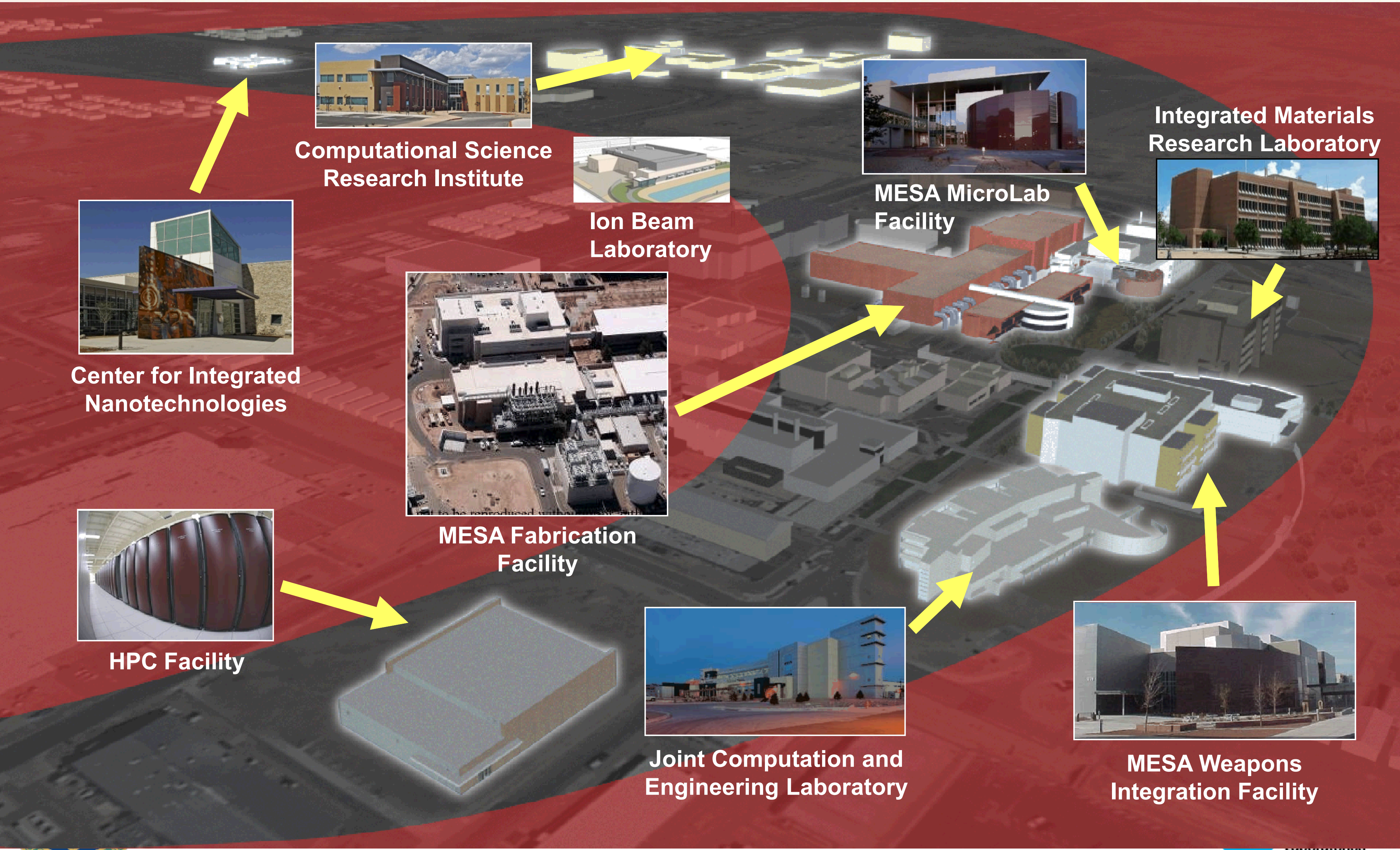
Energy, Climate, & Infrastructure

Homeland Security & Defense

ST&E Supports the Four Mission Areas

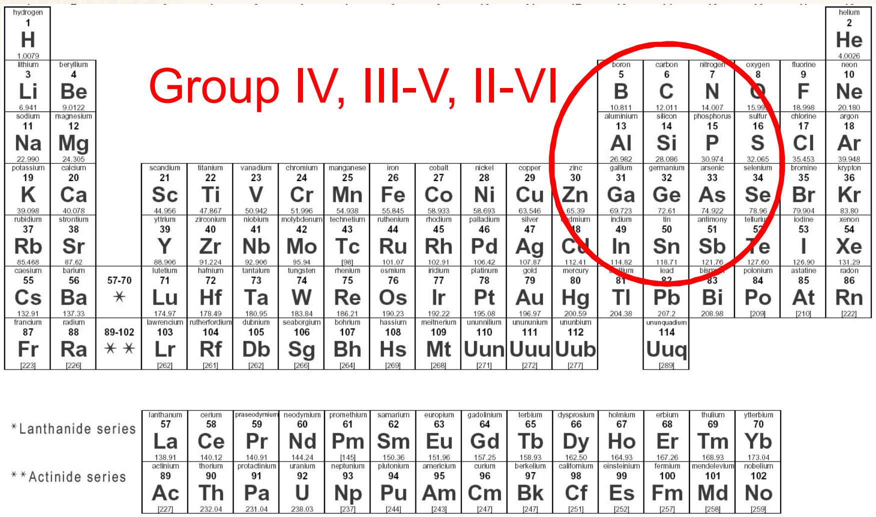
ST&E is a fifth mission & SMU that supports the other four

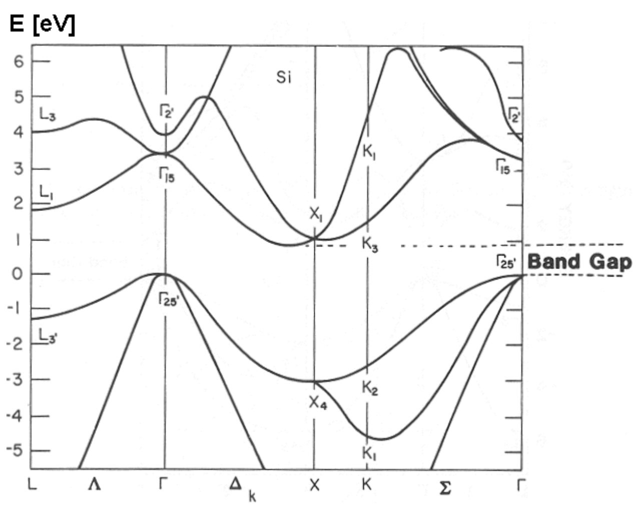
Sandia's Innovation Corridor



What are Semiconductors?

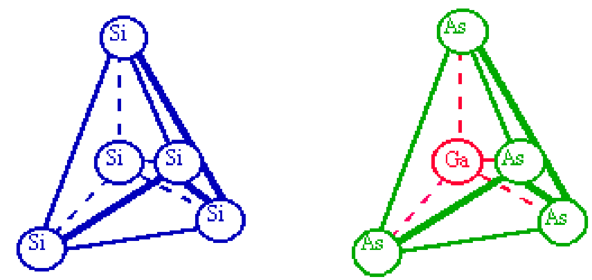
Group IV, III-V, II-VI



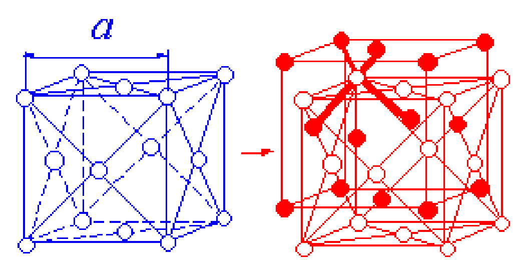


Bandstructure of Si

Tetrahedral bonding configuration



Face Centered Cubic and Diamond Crystal Structure



Diamond, Zincblende, or Hexagonal (e.g. 2H, 4H, 6H) crystal structure

Google images

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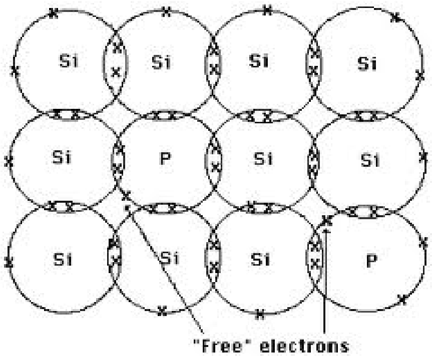
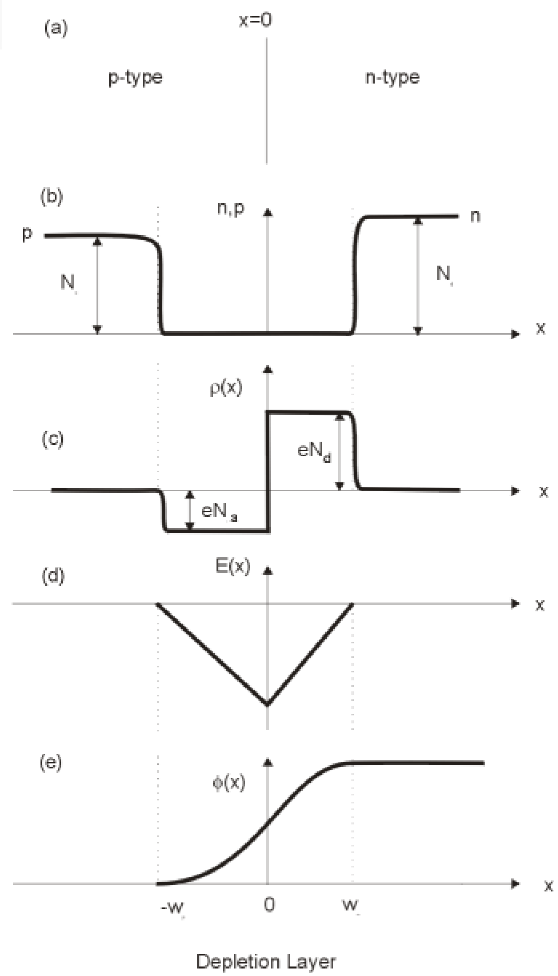
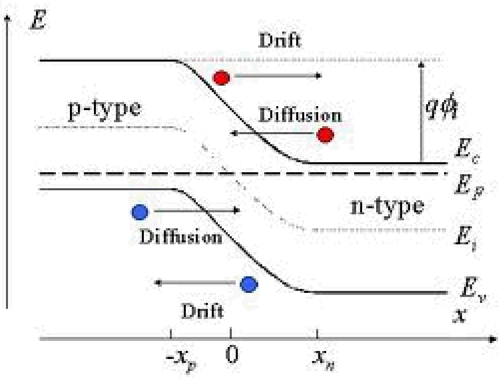
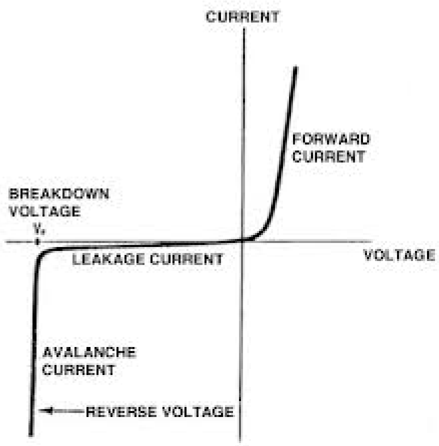
Doping and pn Junctions



Doping of Si:
Extra electron = n-type
Missing electron = p-type







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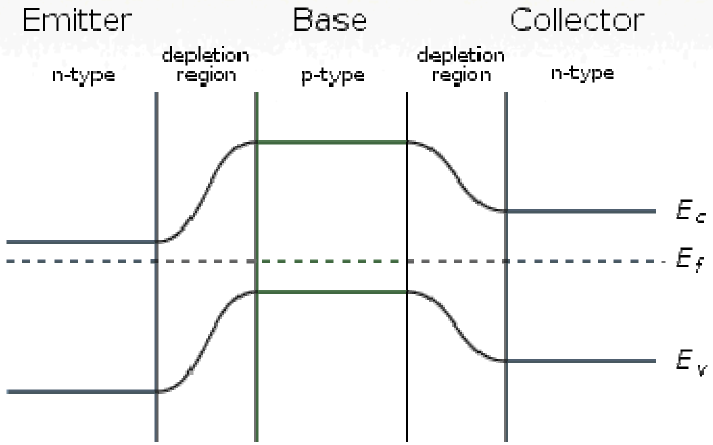
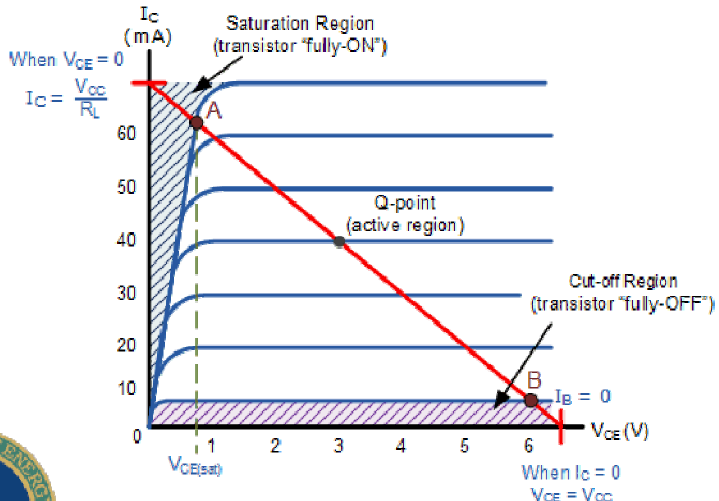
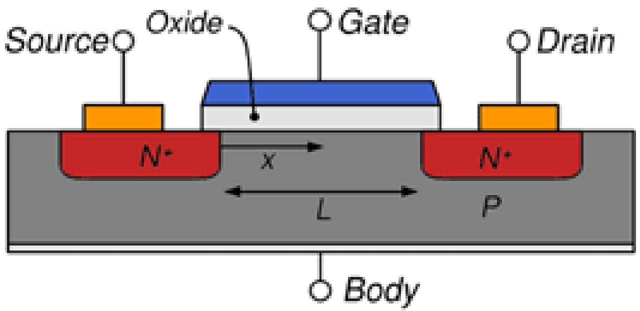
Bipolar and Field-Effect Transistors

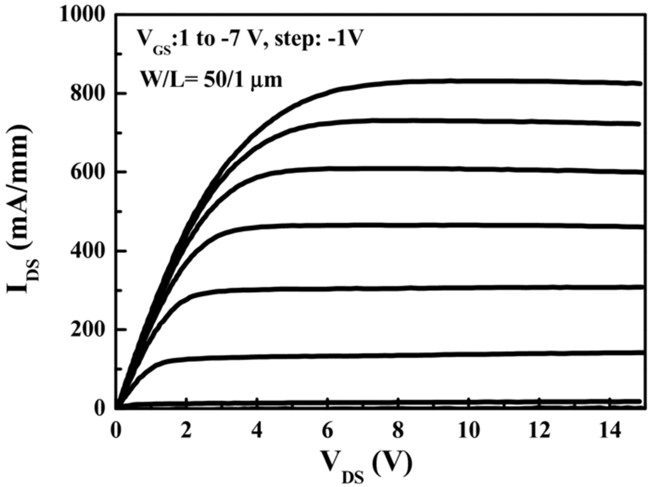
Bipolar





Field-Effect





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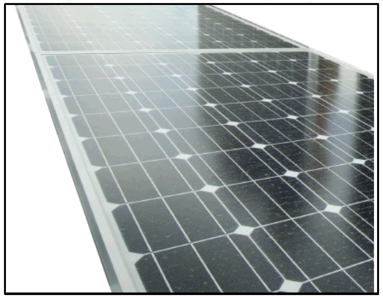
Comparison of Semiconductor Materials

WBG materials allow higher photon energy for optoelectronics, and higher voltage, current, temperature, and frequency for power electronics

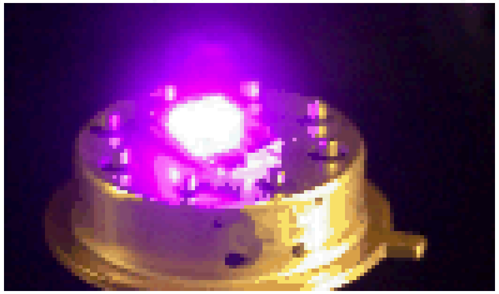
Property	Si	4H-SiC	GaN	Diamond	AlN
Bandgap E_g, (eV)	1.1	3.2	3.4	5.5	6.2
Dielectric constant, ε_r	11.9	10.1	9	5.5	9
Electric breakdown field, E_c (MV/cm)	0.3	2.2	3	10	13
Electron Mobility, μ_n ($cm^2/V\cdot s$)	1500	700	900 (bulk) 2000 (2D)	1900	300
Hole Mobility, μ_p ($cm^2/V\cdot s$)	600	115	150	600	20
Thermal Conductivity, λ (W/cm·K)	1.5	4.9	> 1.3	22	2.9
Saturated Electron Drift Velocity, v_{sat} ($\times 10^7$cm/s)	1	2	2.5	2.7	1.2

WBGs Are Increasingly Critical to Energy Technologies

Transitioning to cleaner and more efficient energy sources will require development and integration of WBG devices



Power electronics and inverters for electric vehicles and the electrical grid



Solid-state lighting

Material	Bandgap (eV)	
Si	1.1	
4H-SiC	3.2	Wide-bandgap (WBG)
GaN	3.4	Wide-bandgap (WBG)
Diamond	5.5	Ultra-wide-bandgap
AlN	6.2	Ultra-wide-bandgap

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WBGs Enable Reductions in Power Loss, Size, and Weight

Device	Brkdwn Voltage	$P_{switching}$ 500 Hz	$P_{switching}$ 5 kHz	$P_{switching}$ 20 kHz	$P_{conduction}$ 100°C
Cree SiC MOSFET	12 kV	4 W/cm^2	40 W/cm^2	160 W/cm^2	100 W/cm^2
ABB Si IGBT	2x6.5 kV	72.5 W/cm^2	725 W/cm^2	2900 W/cm^2	182 W/cm^2

Cree/Powerex/GE

Si IGBT module
13.5 kV, 100 A

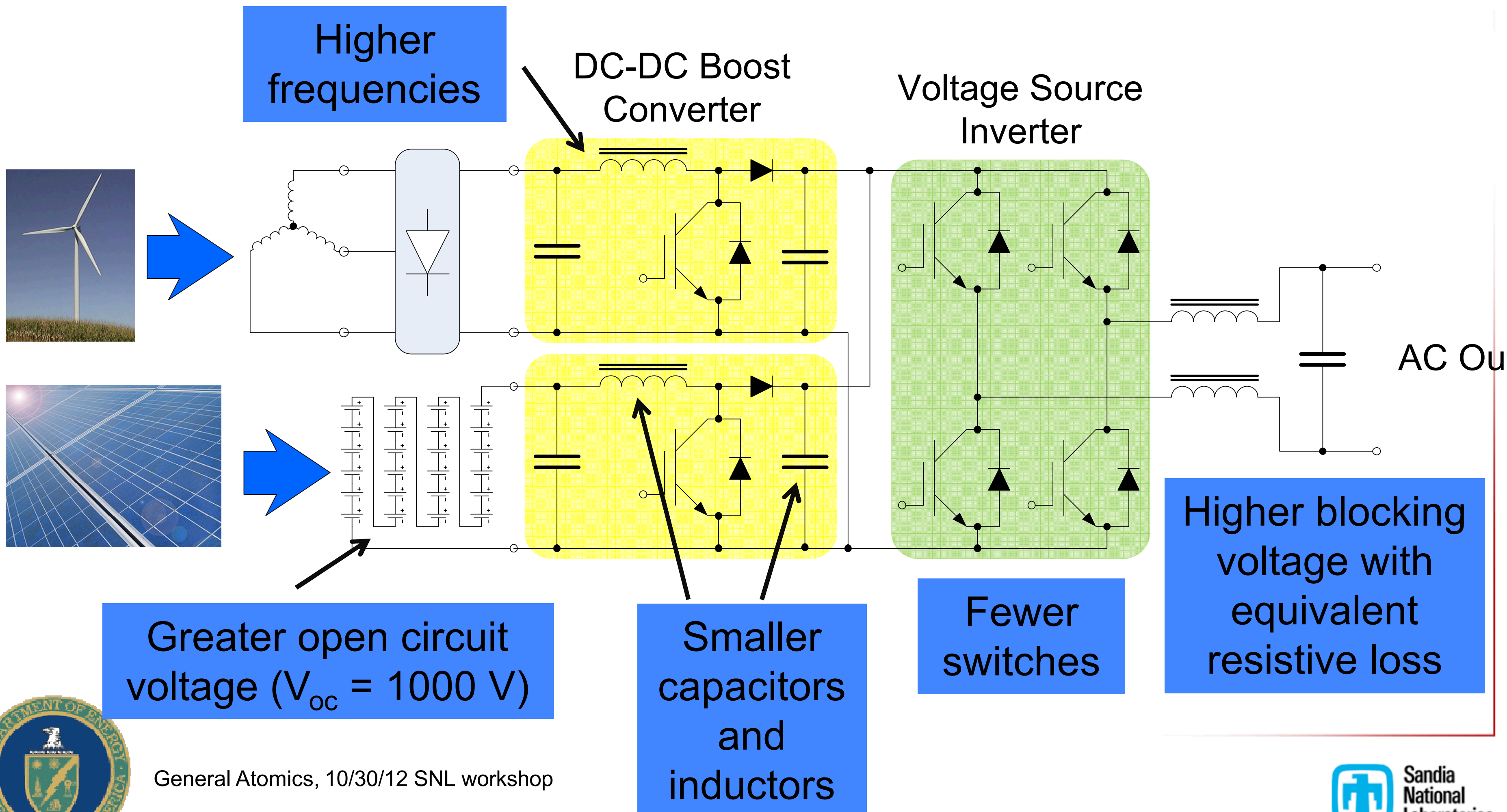
SiC MOSFET module
10 kV, 120 A

SiC MOSFET module is 10% weight and 12% volume of Si IGBT module

M. K. Das et al., ICSCRM 2011

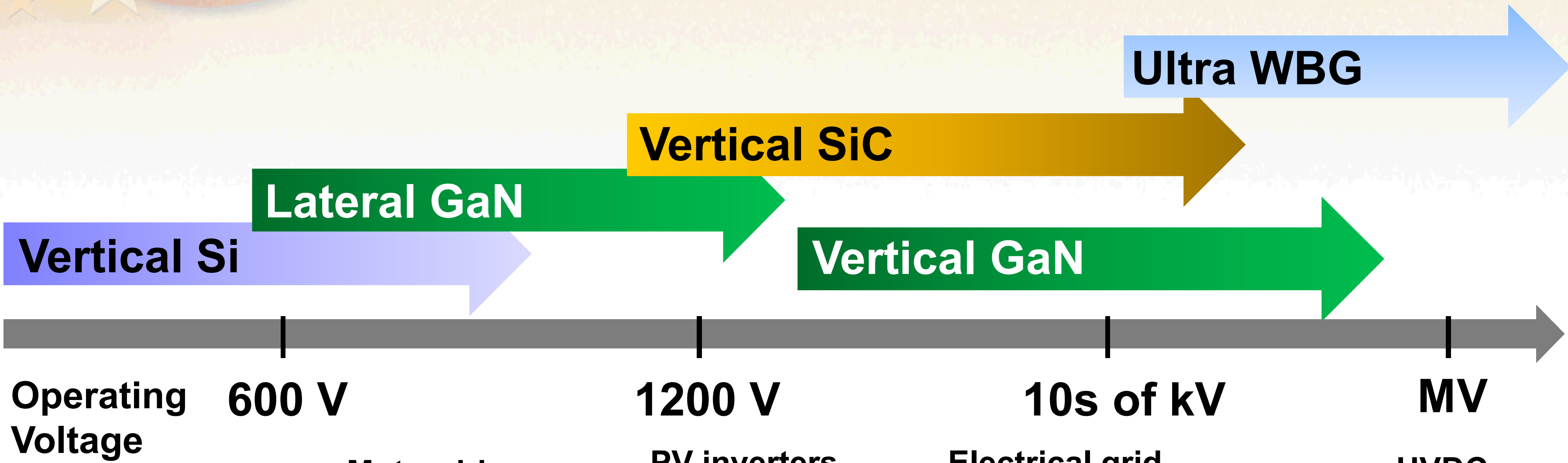
WBGs for Increased Grid Efficiency and Resiliency

A modern, resilient electric grid with integrated renewable power sources requires power electronics and power inverters



General Atomics, 10/30/12 SNL workshop

Application Space for WBG Devices



Motor drives
Electric vehicles
Airplanes

- Reduce or eliminate passive components (capacitors, inductors)
- Spectral purity extends motor lifetime
- Operate at higher temperatures without liquid cooling

PV inverters

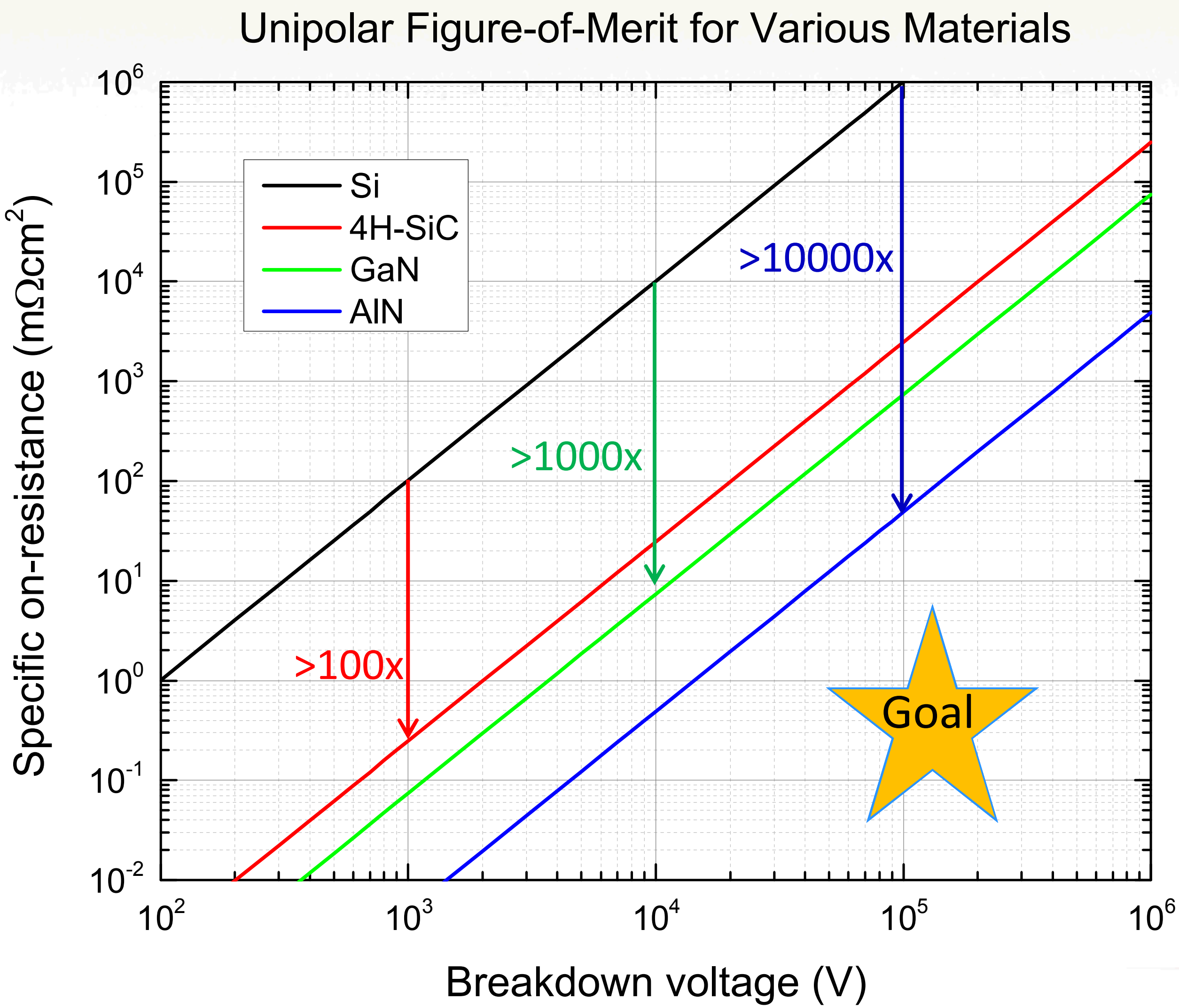
Electrical grid
Electric rail
Grid-level energy storage

- AC subsystems to 13.8 kV

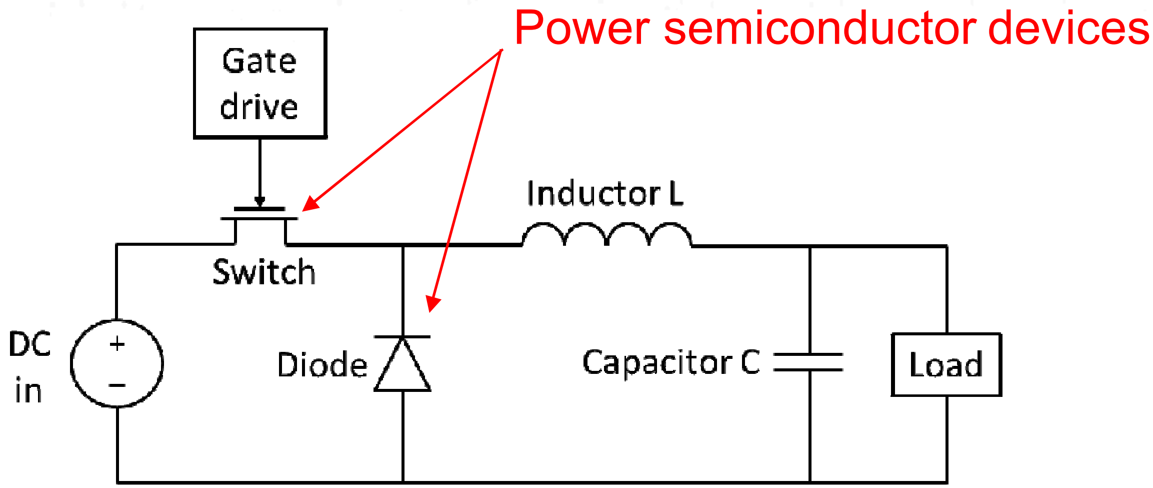
HVDC transmission and fault protection

- Increase grid resiliency
- Less resistive energy loss
- Replace expensive IGBT/IGCT stack

WBGs Offer Orders-of-Magnitude Improvement for PE

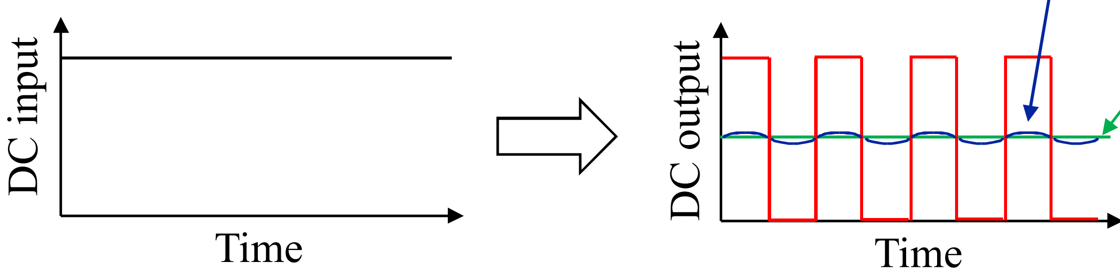


Example Power Electronics Circuit: Step-Down (Buck) DC-to-DC Converter

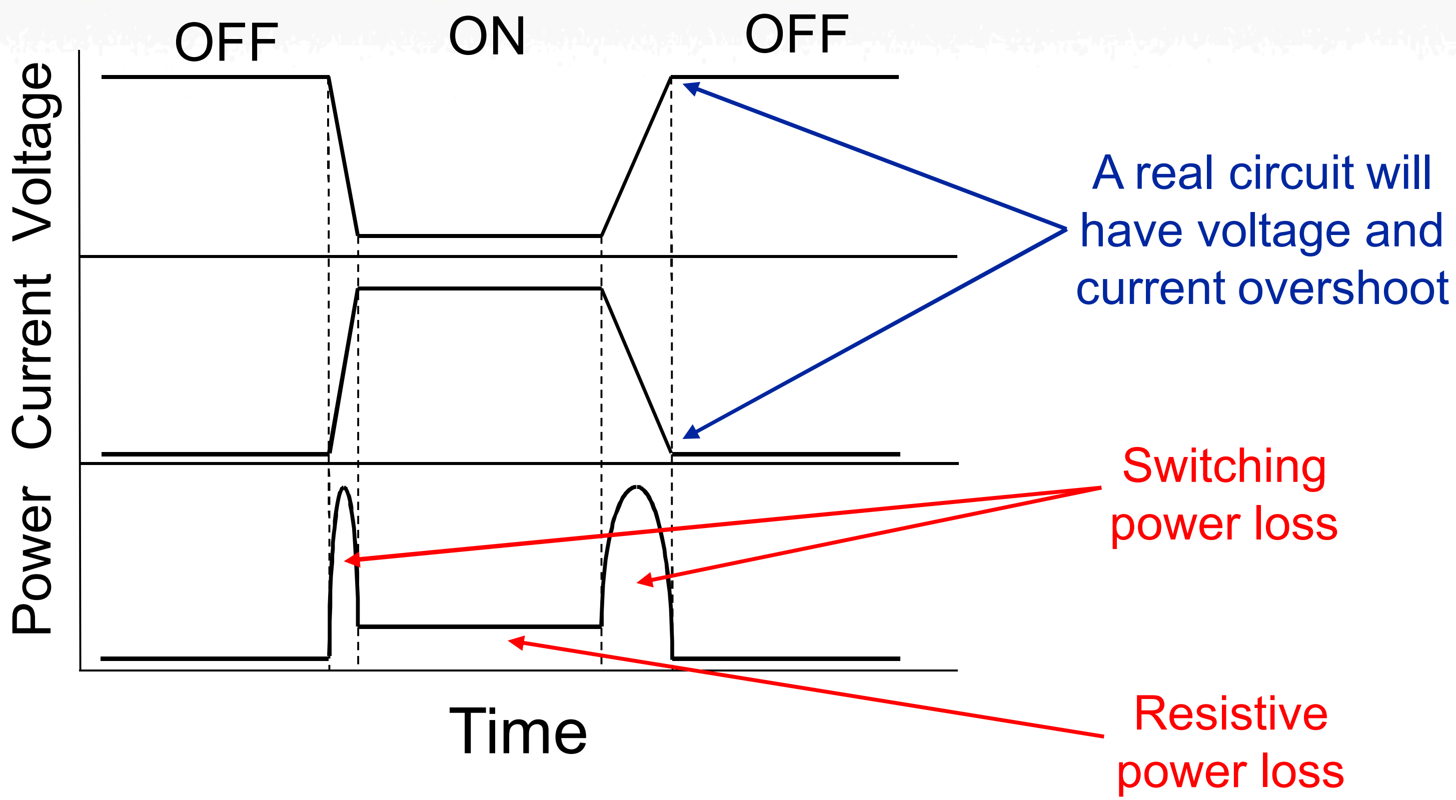


$$\frac{V_{ripple}}{V_{out}} = \frac{1 - D}{8LCf^2}$$

PWM (e.g. 100 kHz)
Duty cycle = D
$V_{out} = DV_{in}$



PE Switch Current, Voltage, and Power Waveforms



Minimum ON-state loss: Low R_{on}
Minimum OFF-state loss: Low leakage
Minimum switching loss: Fast switching transients

Application Classes of Power Devices

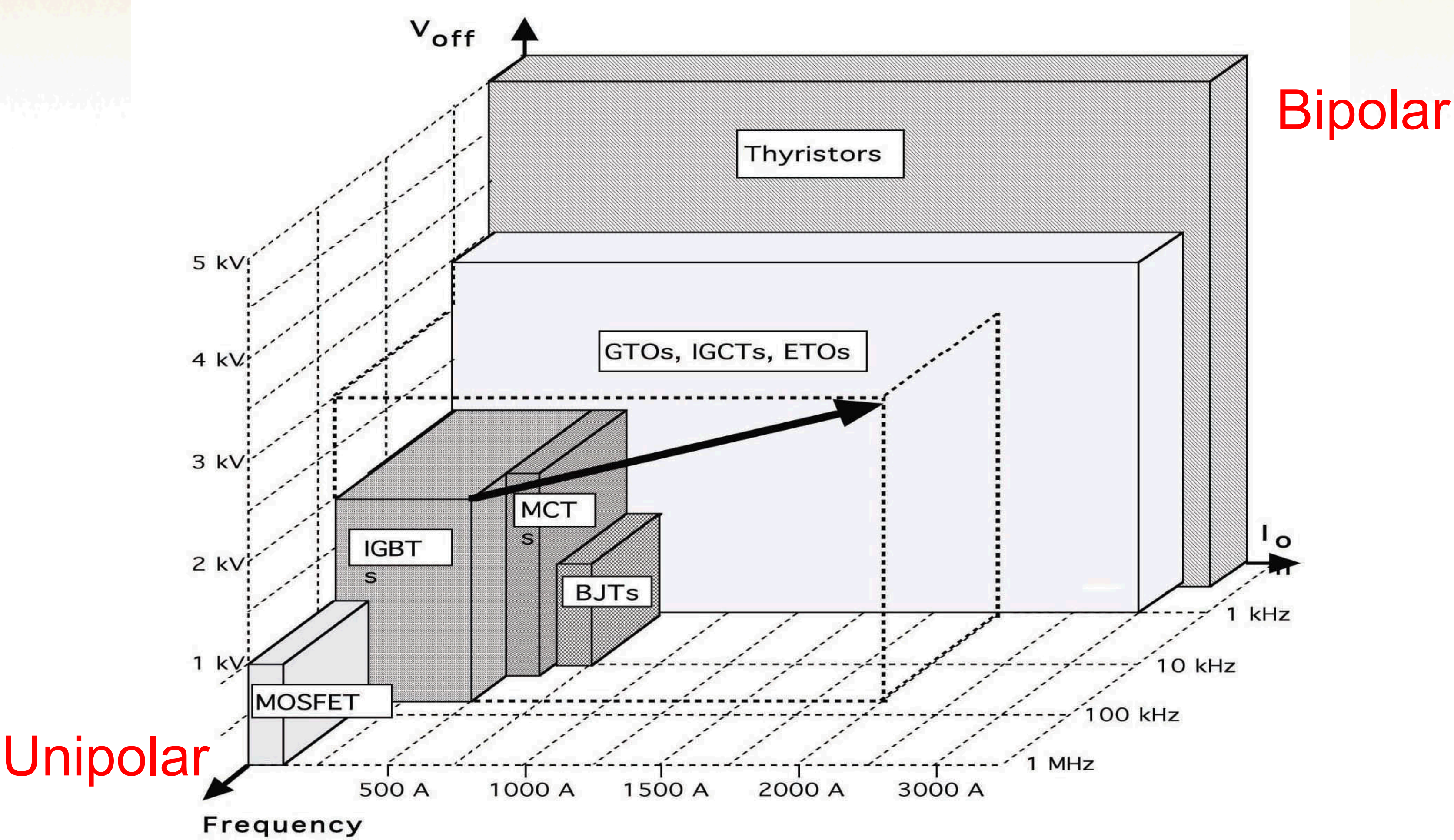
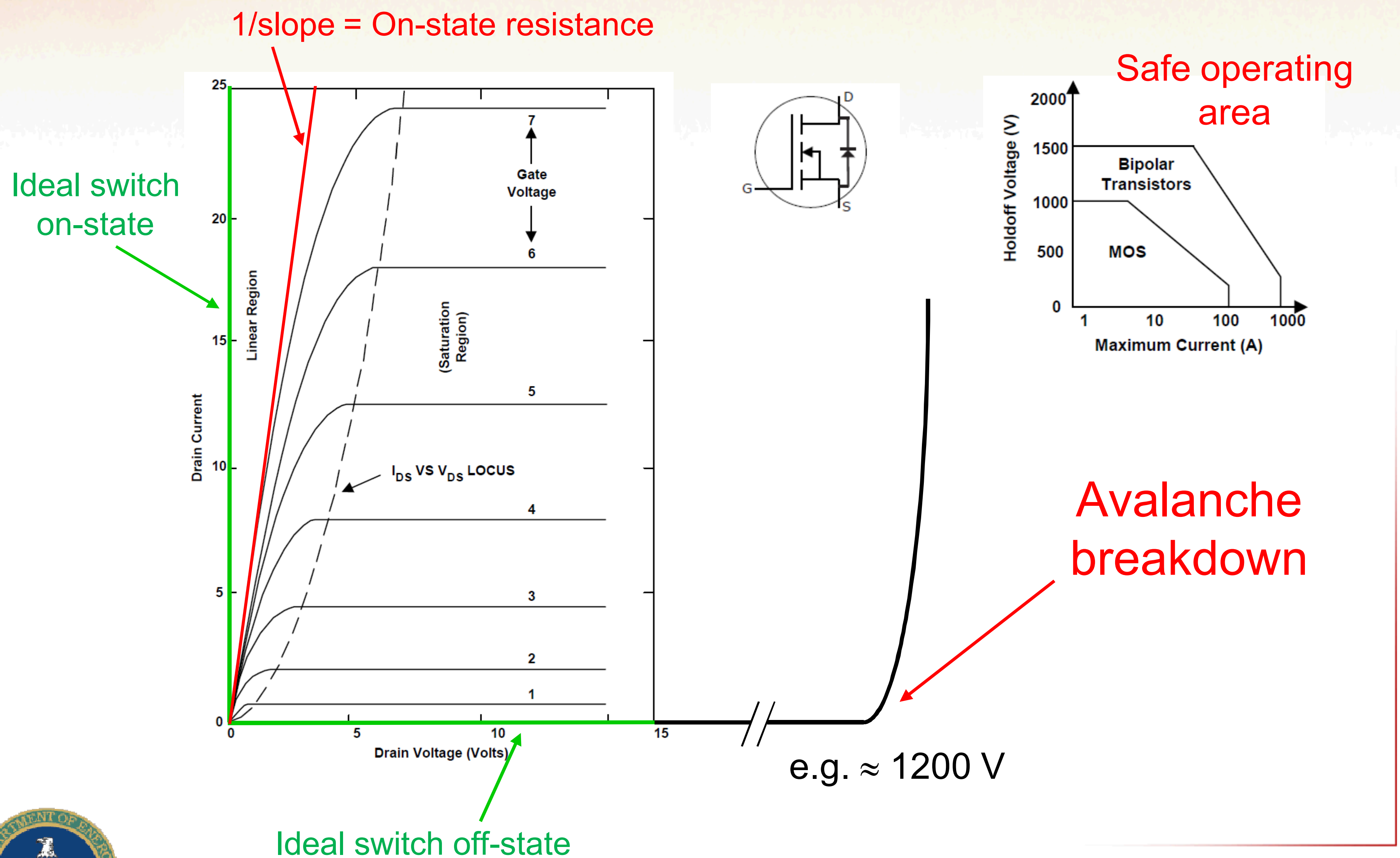


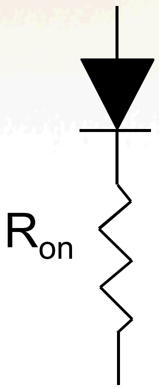
Figure from Mohan et al., “Power electronics: Converters, Applications, and Design” (Wiley, 2003).

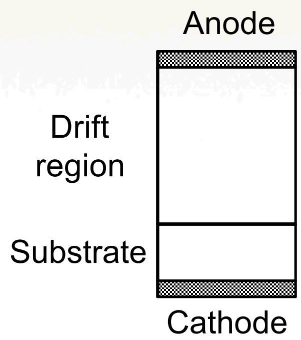
Real Power Devices are NOT Ideal Switches!

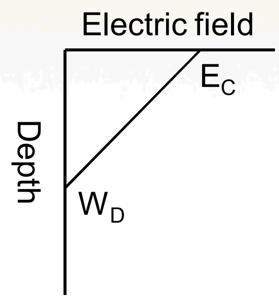


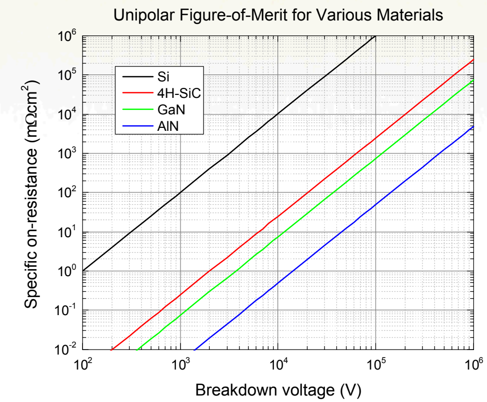
Figures from International Rectifier "Power MOSFET Basics" pamphlet

Unipolar Power Device Figure-of-Merit









- Off-state: Integrate electric field to get breakdown voltage $V_B = W_D E_C/2$ (1)
- Gauss' law: $\varepsilon E_C = qN_D W_D$ (2)
- On-state: Current transport due to carrier drift, resistance $R_{on} = W_D/sA$
  Conductivity $\sigma = q\mu_n n = q\mu_n N_D$ assuming complete dopant ionization
  Specific on-resistance $R_{on,sp} = R_{on}A = W_D/\sigma = W_D/\, q\mu_n N_D$ (3)

- Combining (1) and (2) gives dependence of V_B on N_D and E_C: $V_B = \varepsilon E_C^2/2qN_D$

- Combining (1), (2), and (3) one obtains the unipolar "figure-of-merit":
  $R_{on,sp} = 4V_B^2/\varepsilon\mu_n E_C^3$

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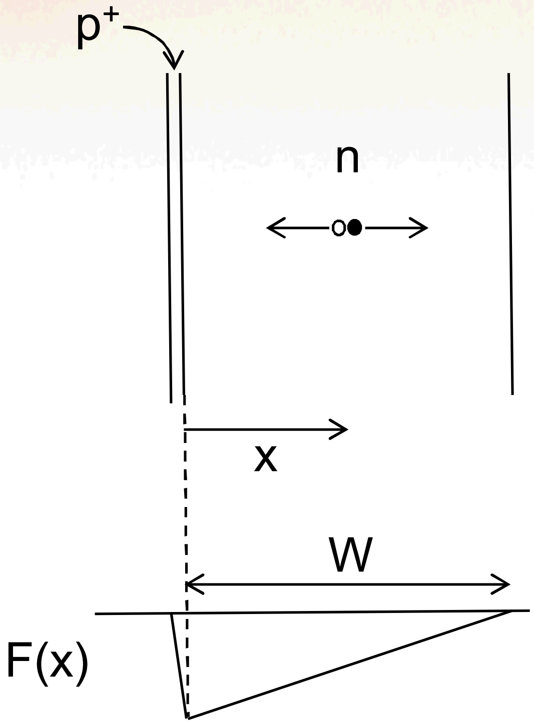
Avalanche Breakdown Physics: Impact Ionization in a Depletion Region



Impact ionization coefficient for electrons, holes = α_n, α_p = # of ehps generated per cm by an incident hot electron, hole; may be defined in terms of generation rate:

$G_{ii} = \alpha_n J_n + \alpha_p J_p$

α_n and α_p are strong functions of electric field!

Suppose that an electron-hole pair is generated at position x. Then the number of ehps N(x) generated at position x is (1):

$$N(x) = 1 + \int_0^x \alpha_p N(x')dx' + \int_x^W \alpha_n N(x')dx'$$

This can be differentiated to give:

$$\frac{dN}{dx} = (\alpha_p - \alpha_n)N(x)$$

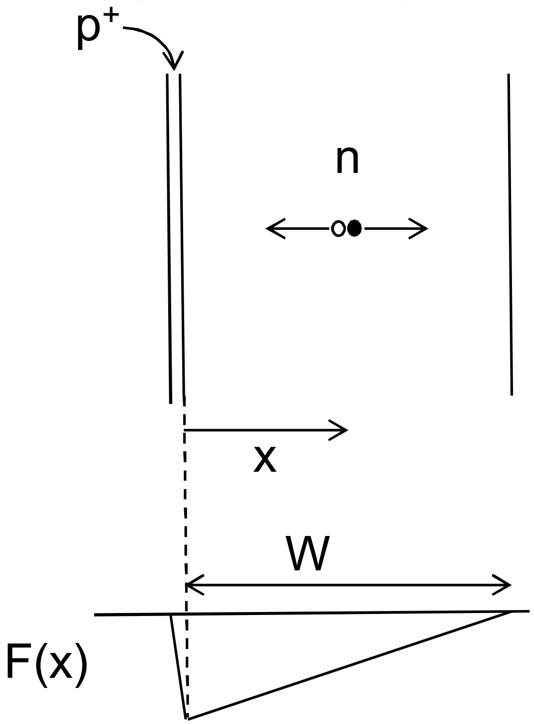
The solution of the differential equation is:

$$N(x) = N(0)exp\left[\int_0^x (\alpha_p - \alpha_n)dx'\right]$$

1.) R. J. McIntyre, “Multiplication Noise in Uniform Avalanche Diodes,” IEEE Trans. Elec. Dev. **13(1)**, 164 (1966).

Criterion for Avalanche Breakdown

The equations may be combined to give (after some algebra):



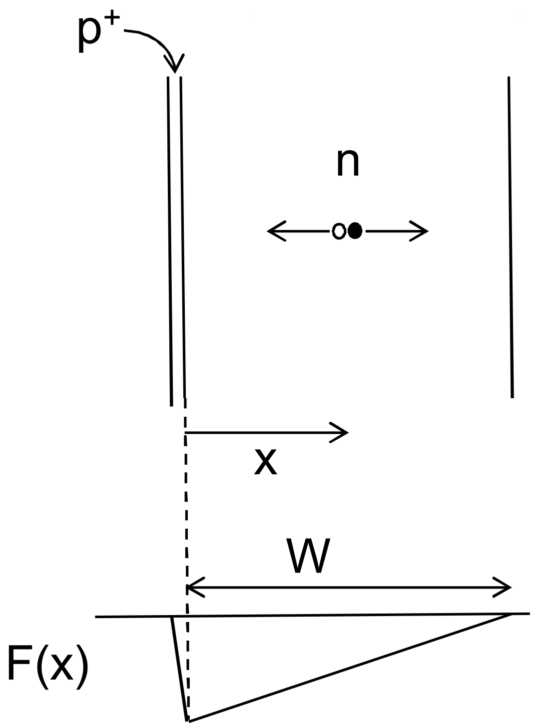
$$N(x) = \frac{exp\left[\int_0^x (\alpha_p - \alpha_n) dx'\right]}{1 - \int_0^W \alpha_n exp\left[\int_0^x (\alpha_p - \alpha_n) dx'\right] dx}$$

Avalanche breakdown occurs when the number of generated ehps tends to infinity, i.e. when the denominator goes to zero:

$$\int_0^W \alpha_n exp\left[\int_0^x (\alpha_p - \alpha_n) dx'\right] dx = 1$$

Since α_n and α_p are such strong functions of electric field, in practice this always occurs near the location of peak field, and the majority of the contribution to the integral is from a small volume near this point (i.e. at the junction).

Approximations for Analytical Solutions



The approximation that α_n and α_p are proportional is often used: $\alpha_p = \gamma\alpha_n$ in which case the ionization integral reduces to:

$$\int_0^W \frac{\alpha_p - \alpha_n}{\ln(\alpha_p/\alpha_n)}\,dx = \int_0^W \alpha_{eff}\,dx = 1$$

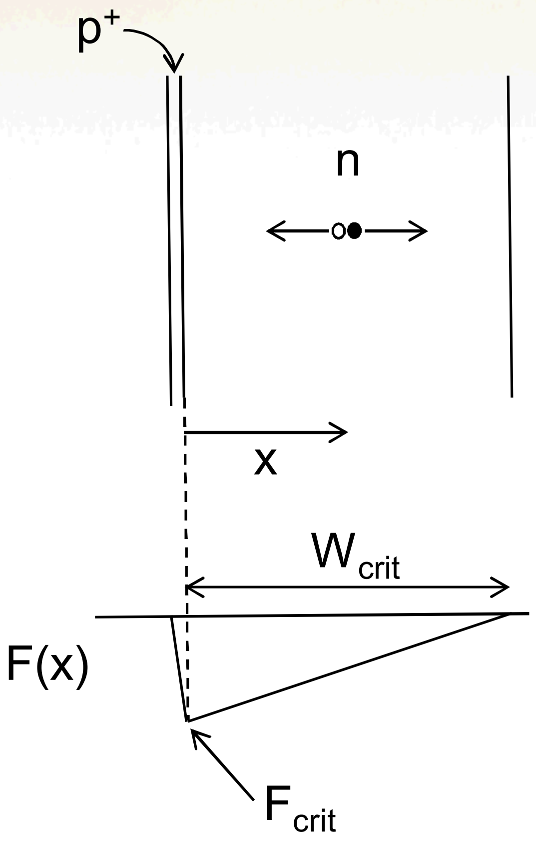
The “effective” impact ionization rate is often empirically modeled as $\alpha_{eff} = \alpha_{eff,0}F^7$

Finally, for a uniformly doped single-sided pn junction, the electric field is given by:

$$F(x) = -\frac{qN_D W}{\varepsilon}\left(1 - \frac{x}{W}\right)$$

The last expression is important for the definition of the “critical field”.

What is the "Critical Field"?



The critical field is defined as the maximum magnitude electric field in a uniformly doped, one-sided pn junction at the point when avalanche breakdown is initiated:

$$\int_0^W \alpha_{eff}\left[F_{crit}\left(1-\frac{x}{W_{crit}}\right)\right]dx \approx \int_0^W \alpha_{eff,0}\,F_{crit}{}^7\left(1-\frac{x}{W_{crit}}\right)^7 dx = 1$$

with $F_{crit} = qN_D W_{crit}/\varepsilon$

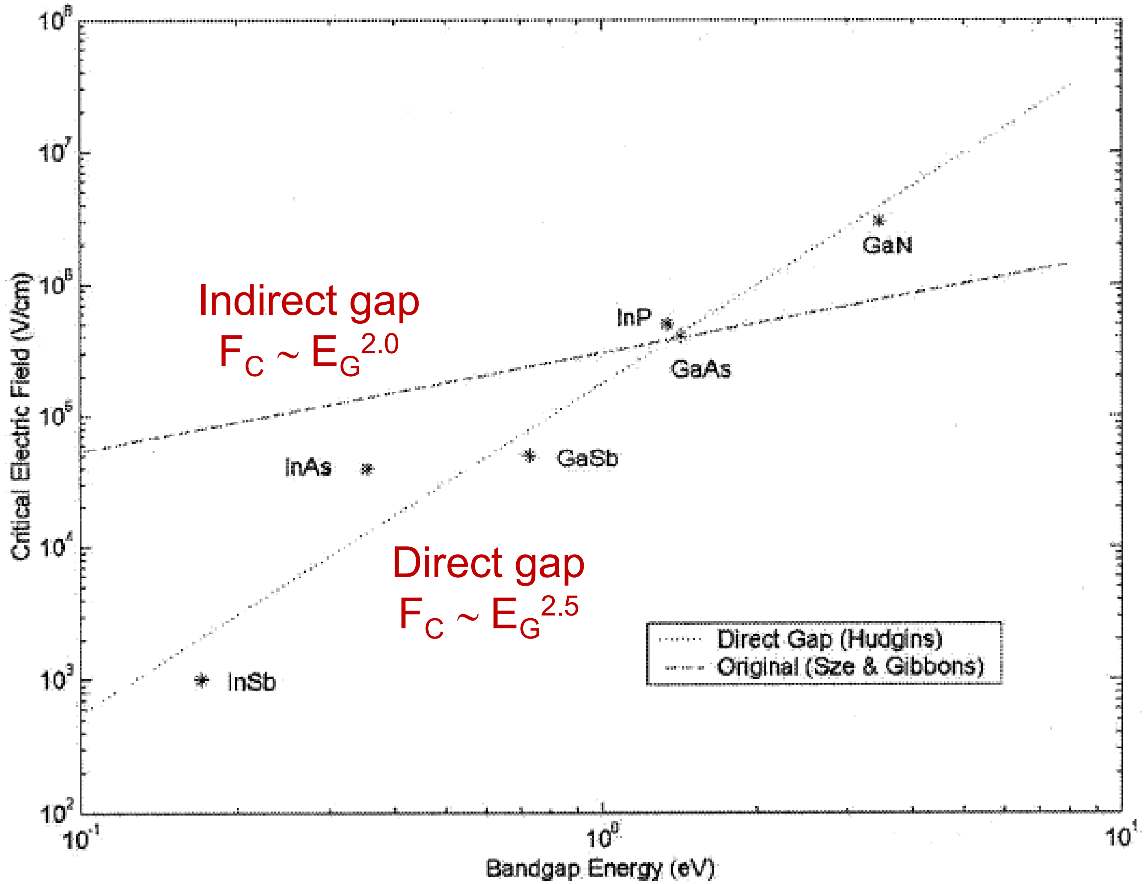
Performing the integral gives:

$$F_{crit}=(8qN_D/\alpha_{eff,0}\varepsilon)^{1/8}$$

Note that this is doping-dependent, but this is a weak dependence (and highly approximate) and in practice F_{crit} is taken to be constant.

Critical fields for:
Si: 0.2 MV/cm
4H-SiC: 2 MV/cm
GaN: 3 MV/cm

Dependence of Critical Field on Bandgap



J. L. Hudgins, G. S. Simin, E. Santi, and M. A. Khan, "An Assessment of Wide Bandgap Semiconductors for Power Devices," IEEE Trans. on Elect. Dev. **18(3)**, 907 (2003).

Analytical Models for Impact Ionization Coefficients

The most widely used model for impact ionization by device engineers is due to Shockley (1), and is based on the "lucky electron" idea in which electron avoid scattering events until the threshold energy is attained. This results in:

$$\alpha_{n,p}(F) = a_{n,p} exp(-b_{n,p}/F)$$

An alternative theory was proposed by Wolff (2) in which impact ionization occurs due to carriers in the high-energy tail (above E_{th}) of a shifted Maxwellian distribution (electrons undergo numerous collisions, which is essentially the opposite view of Shockley):

$$\alpha_{n,p}(F) = a_{n,p} exp(-b_{n,p}/F^2)$$

Numerous other papers (e.g. 3, 4) have been published expanding upon these theories. However, in practice the Shockley expression dominates the power electronics world. ***Is this expression appropriate for WBG semiconductors?***

1.) W. Shockley, "Problems Related to pn Junctions in Silicon," Solid-State Electronics **2**, 35 (1961).
2.) P. A. Wolff, "Theory of Electron Multiplication in Silicon and Germanium," Phys. Rev. **95**, 1415 (1954).
3.) G. M. Baraff, "Distribution functions and Ionization Rates for Hot Electrons in Semiconductors," Phys. Rev. **128**, 2507 (1962).
4.) H. Shichijo and K. Hess, "Band-Structure Dependent Transport and Impact Ionization in GaAs," Phys. Rev. B **23**, 4197 (1981).

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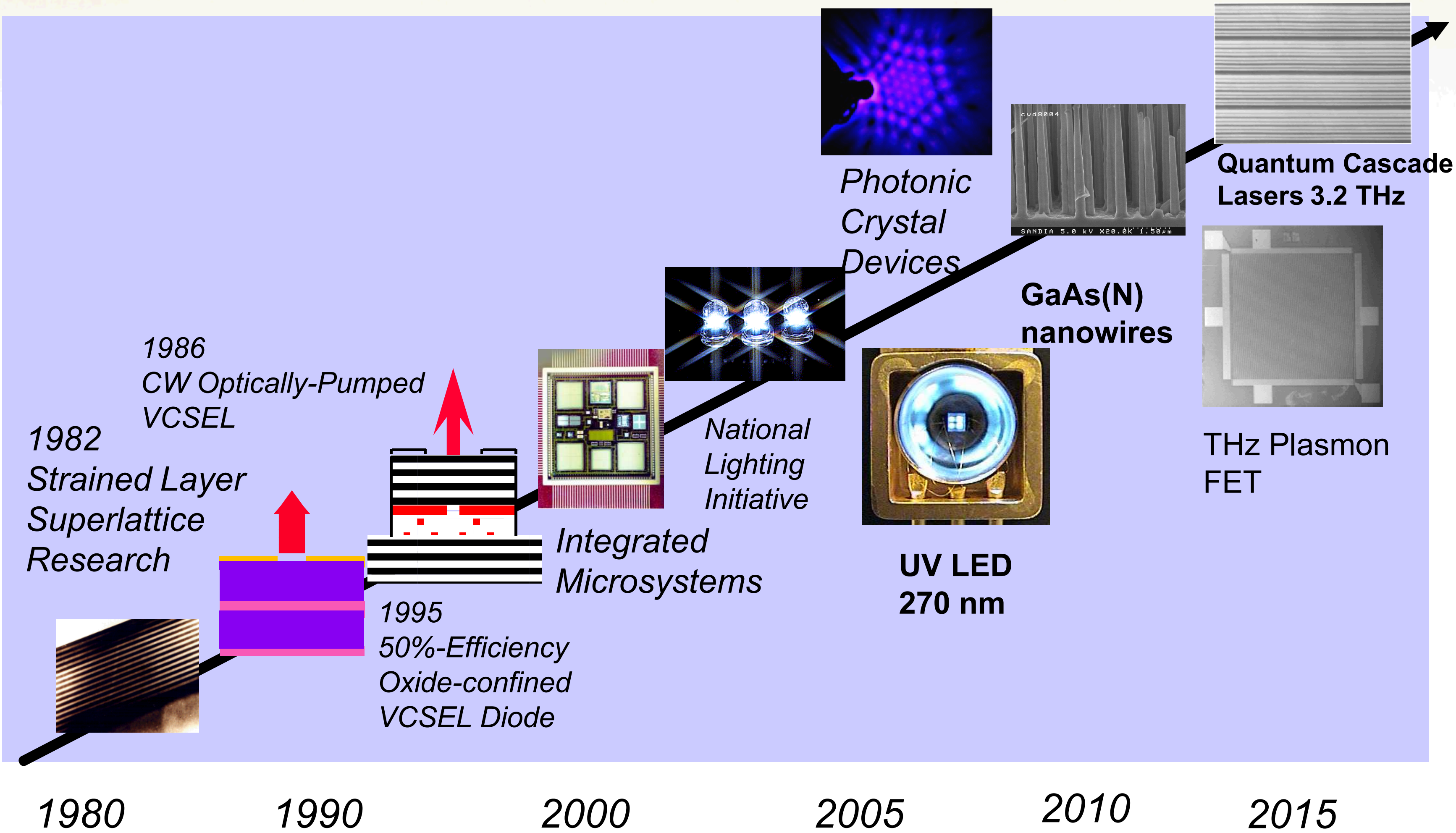
SNL 1980-2012: 30+ Years of Compound Semiconductor S&T



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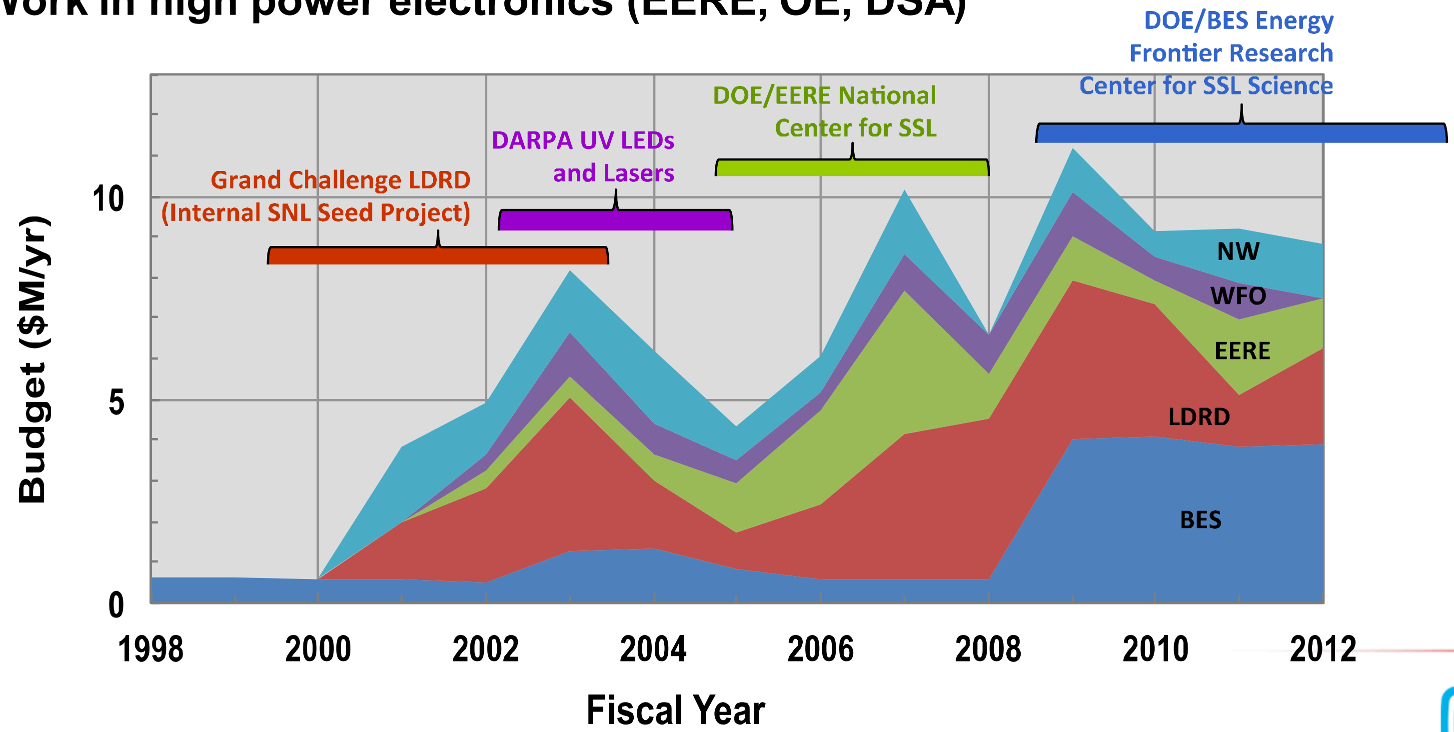
Significant Ongoing Activity in Wide Bandgaps

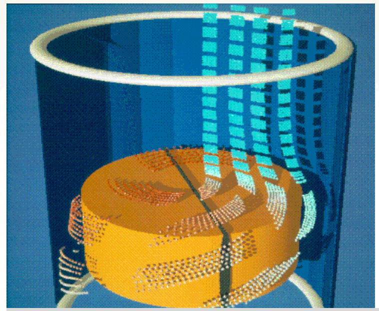
- 40-year history of, and recognized complex-wide as leader in, semiconductor materials and device R&D
- Strong culture of collaboration with industry
- 15 years of pioneering GaN-based materials and devices
  - SSL: Wide recognition of SNL as lead DOE lab; $18M EFRC (SC, EERE)
  - Work in UV optoelectronics (NW, DSA)
  - Work in high power electronics (EERE, OE, DSA)



2009 – Present: Energy Frontier Research Center for SSL Science

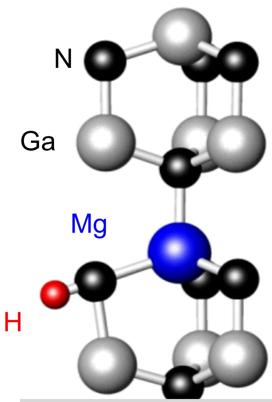
SSLS EFRC
SOLID-STATE LIGHTING SCIENCE
ENERGY FRONTIER RESEARCH CENTER

Chemical Vapor Deposition Sciences



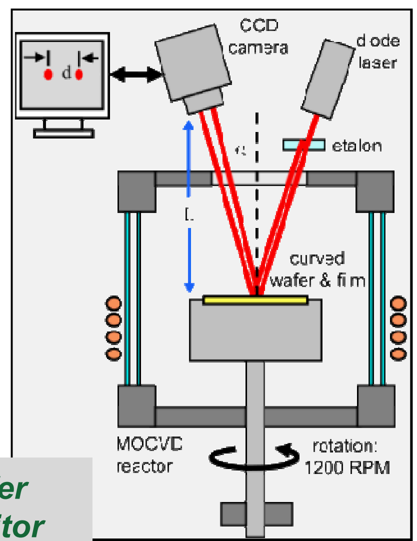
Modeling of chemically reacting reactor flows

Defects in GaN Semi-conductors



DFT calculations of defect energies

Advanced Growth & Science of Epitaxy



In-situ wafer stress monitor

Part of Sandia's SSLS EFRC team

THE UNIVERSITY of NEW MEXICO

Los Alamos NATIONAL LABORATORY

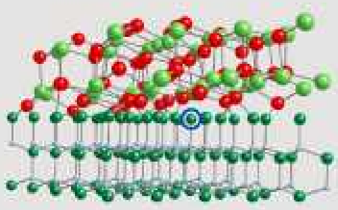
PHILIPS

Yale UNIVERSITY

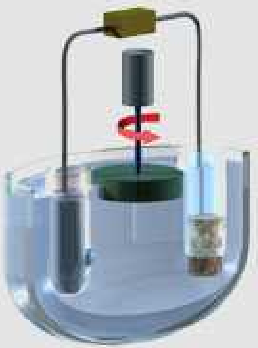
WBG PE Under Sandia's Energy Storage Program

Funded by DOE Energy Storage Program (Dr. Imre Gyuk)
Sandia's Energy Storage PE Program led by Dr. Stan Atcitty

Materials R&D

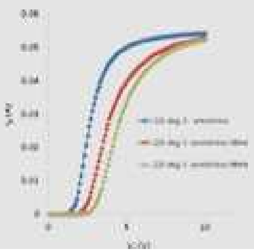


- Gate Oxide R&D
- Bulk GaN



Semiconductor devices

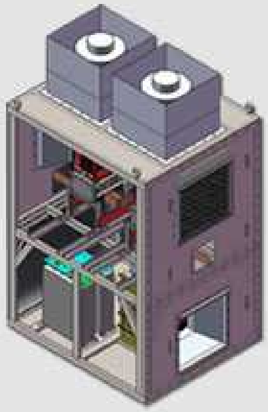
- Post Si Characterization & Reliability
- SiC Thyristors
- ETO



Power Modules

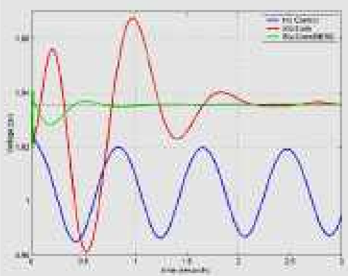
- High Temp/density Power Module

Power Conversion System

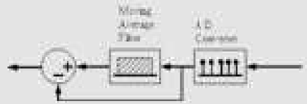


- Dstatcom plus energy storage for wind energy
- Optically isolated MW Inverter
- High density inverter with integrated thermal management
- High temp power inverter

Applications



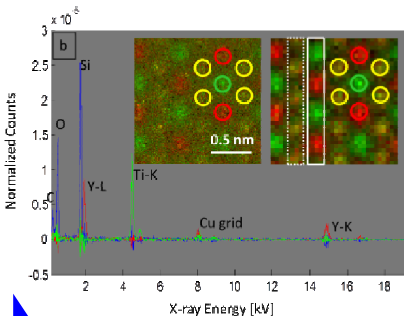
- Power smoothing and control for renewables
- FACTS and Energy Storage



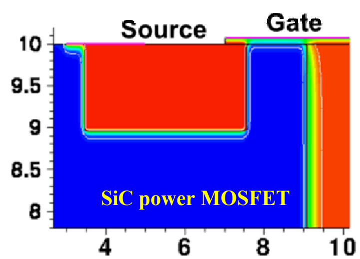
SNL has Extensive R&D Capabilities in Wide Bandgaps – Materials, Devices, and Systems

- **60+ years as DOE/NNSA mission lead in electronics**
- **30+ years of compound semiconductor research**
- **20+ years of wide band gap materials & device R&D**
- **Facilities:** ~30,000 ft^2 clean room (MESA facility); Solid-State Lighting EFRC; microgrid testbed (DETL facility); ASIC design & fab; extensive reliability testing and failure analysis

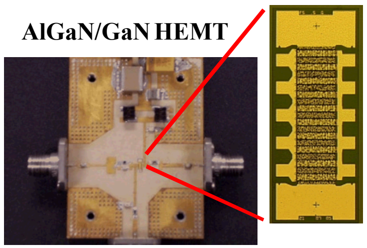
Atomic scale



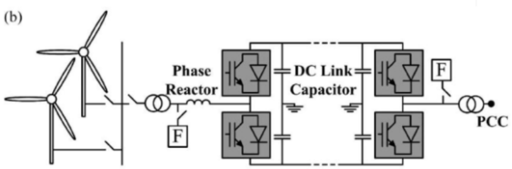
Atomic-resolution characterization



Material and device simulation



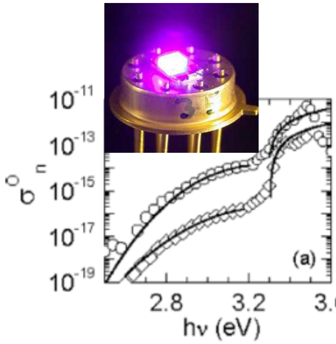
Device fabrication (MESA fab)



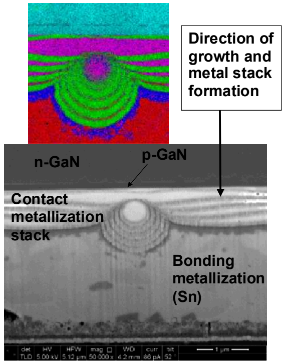
Power circuits and systems

Grid scale

Epitaxial growth



Defect spectroscopy



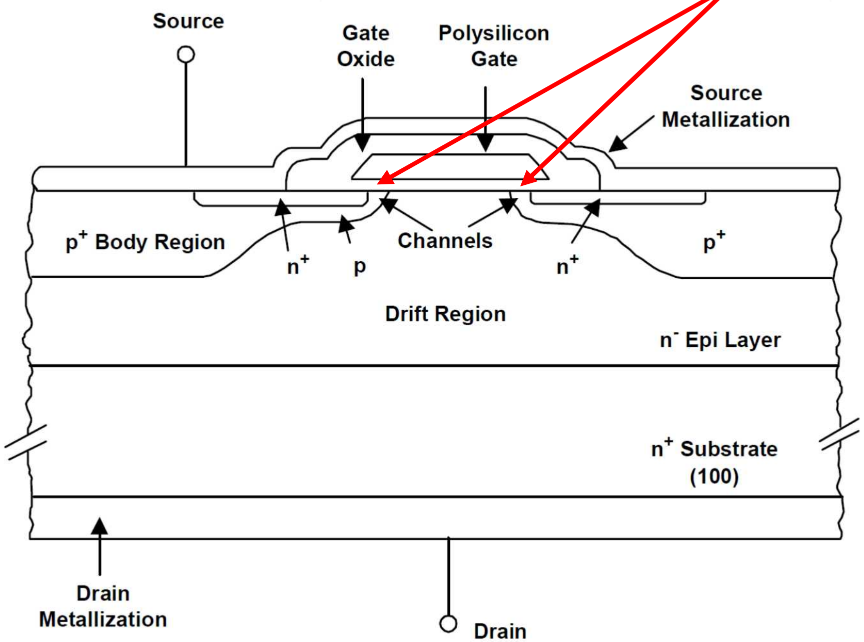
Reliability physics

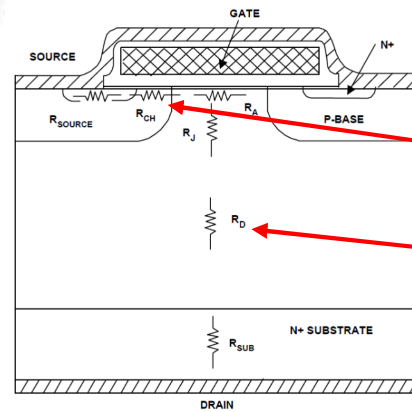
Grid-level power networks (DETL)

Sandia National Laboratories

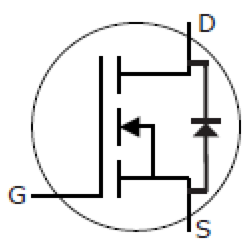
WBG Research at Sandia: SiC Power MOSFET Reliability

Critical gate oxide interfacial region





Channel resistance can dominate drift region resistance



Charge injection due to small band offset at SiO_2/SiC interface enhances V_T shift

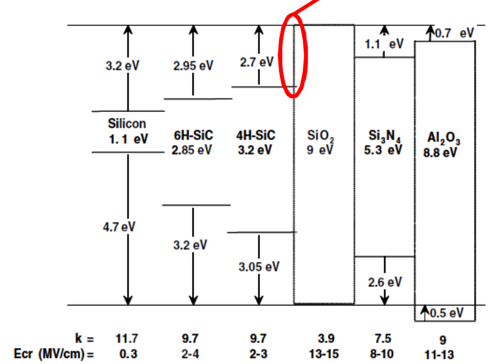


Fig. 1. Dielectric constants, and critical electric fields of various semiconductors (Si, 6H-SiC, 4H-SiC) and dielectrics (SiO_2, Si_3N_4 and Al_2O_3). Conduction and valence band offsets of these are also shown with respect to SiO_2.

R. Singh, Microelectronics Reliability, v. 46, p. 713 (2006).

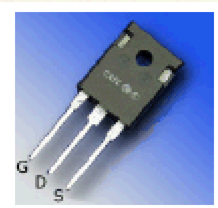
Figures from International Rectifier "Power MOSFET Basics" pamphlet

Sandia National Laboratories

SiC MOSFET Gate Voltage Stress at High T

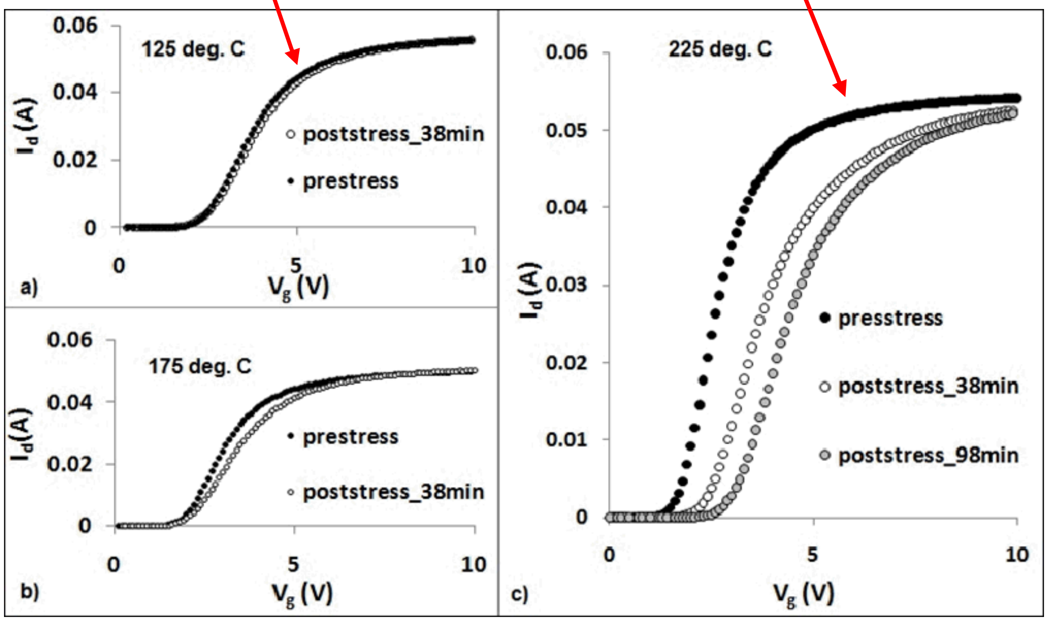
Minimal degradation at rated temp.

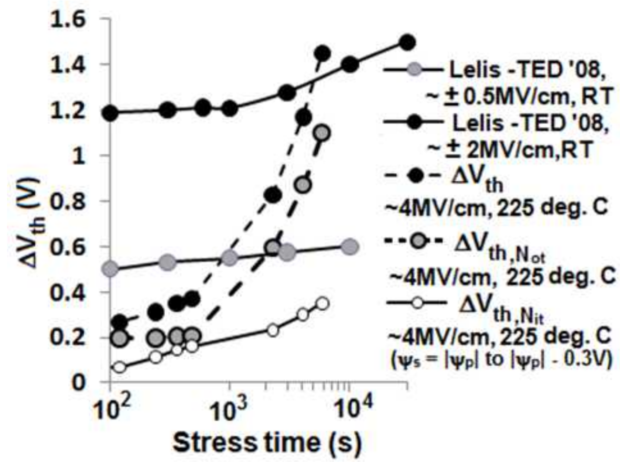
Severe degradation at high temp.



TO-247-3

Commercial 1200 V SiC MOSFET





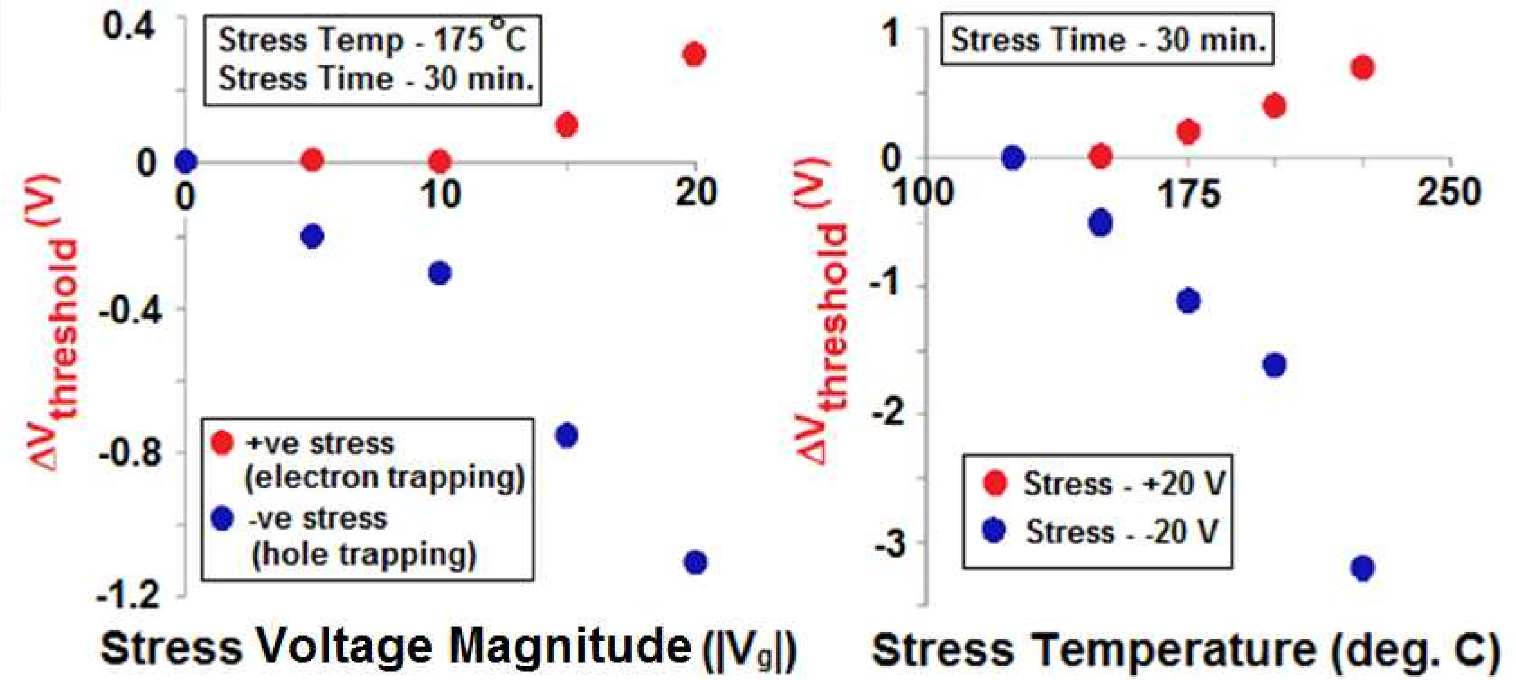
Stress: V_{GS} = +20 V, V_{DS} = 0.1 V

Evolution of interface and bulk trapping components vs. time

S. DasGupta et al., *Applied Physics Letters* **99**, 023503 (2011)

Sandia National Laboratories

SiC MOSFET Electron vs. Hole Trapping



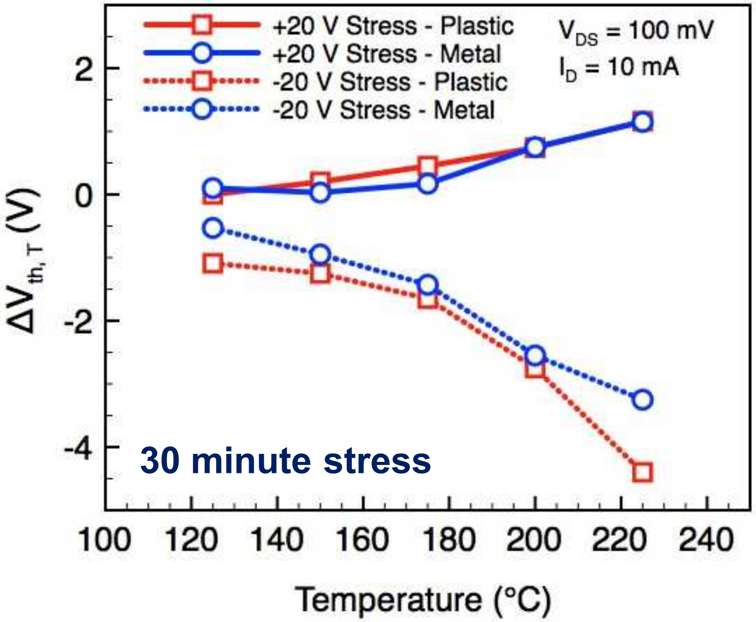
- No V_{th} instability up to 125°C over $V_g = \pm 20$ V
- Hole trapping is more efficient than electron trapping for a given bias and temperature
- Both kinds of trapping are completely recoverable under opposite bias and same temperature

S. DasGupta et al., *Proceedings of the 50th IRPS*, 3D.3 (2012)

SiC Power MOSFET Threshold Voltage Instability

Plastic

Metal



Threshold voltage shift is independent of packaging type

- Shift in threshold voltage ΔV_T (likely due to charge trapping in the gate oxide) will change R_{ON} and thus the ON-state conduction power loss
- ΔV_T is a function of time t, gate voltage V_G, and temperature T
- Assume a power-law dependence on t and V_G, and an Arrhenius dependence on T
- **For *positive* V_G:**
  $\Delta V_T = 8.5\times10^{-3} t^{0.40} V_G^{3.8} \exp(-0.34/kT)$
- **For *negative* V_G:**
  $\Delta V_T = -1.4\times10^{2} t^{0.42} |V_G|^{0.79} \exp(-0.33/kT)$

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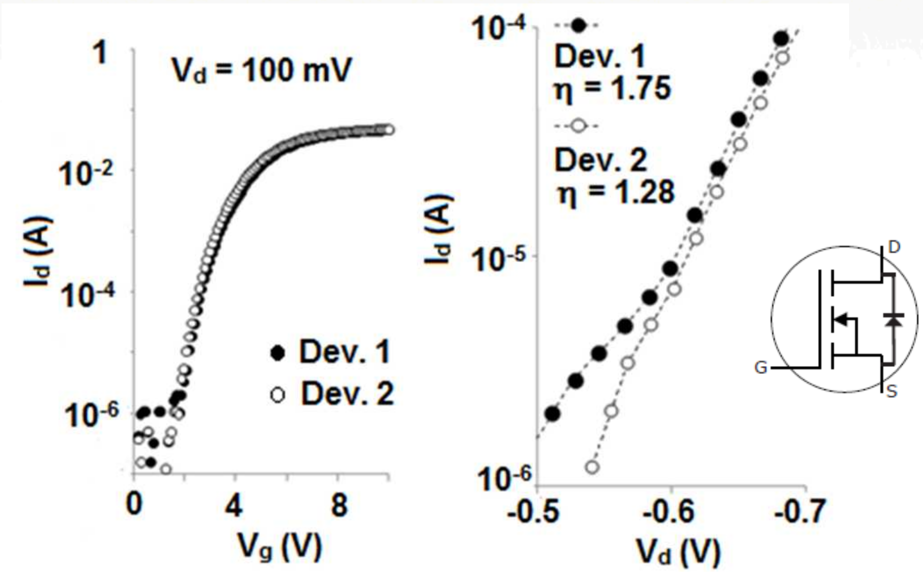
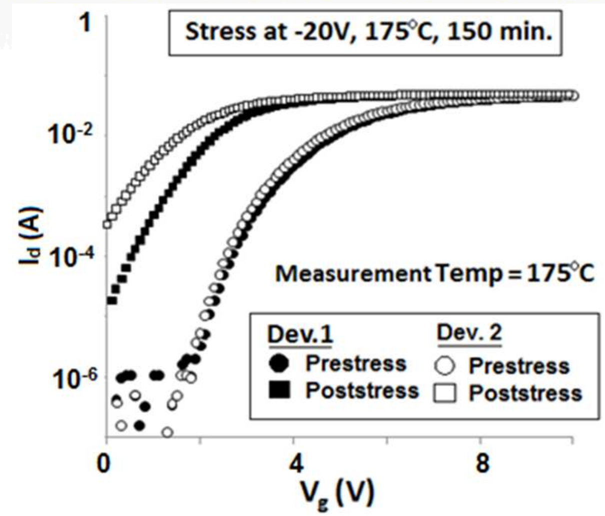
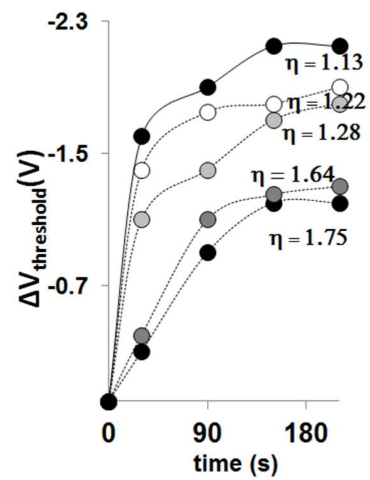
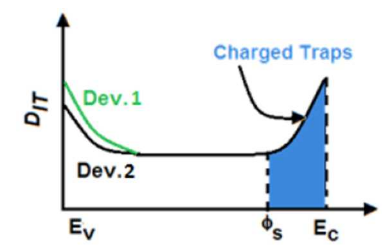
Integrated Free-Wheeling Diode Characteristics and Hole Trapping





SiC MOSFETs with nearly identical I_D-V_{GS} curves show differences in free-wheeling diode ideality factor; higher η devices show more hole trapping for given stress condition

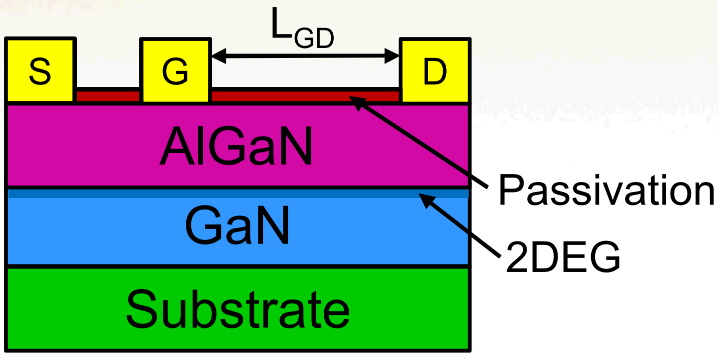




Interface traps are neutral when filled

S. DasGupta et al., *Proceedings of the 50th IRPS*, 3D.3 (2012)

High-Voltage AlGaN/GaN HEMTs



High Electron Mobility Transistor:

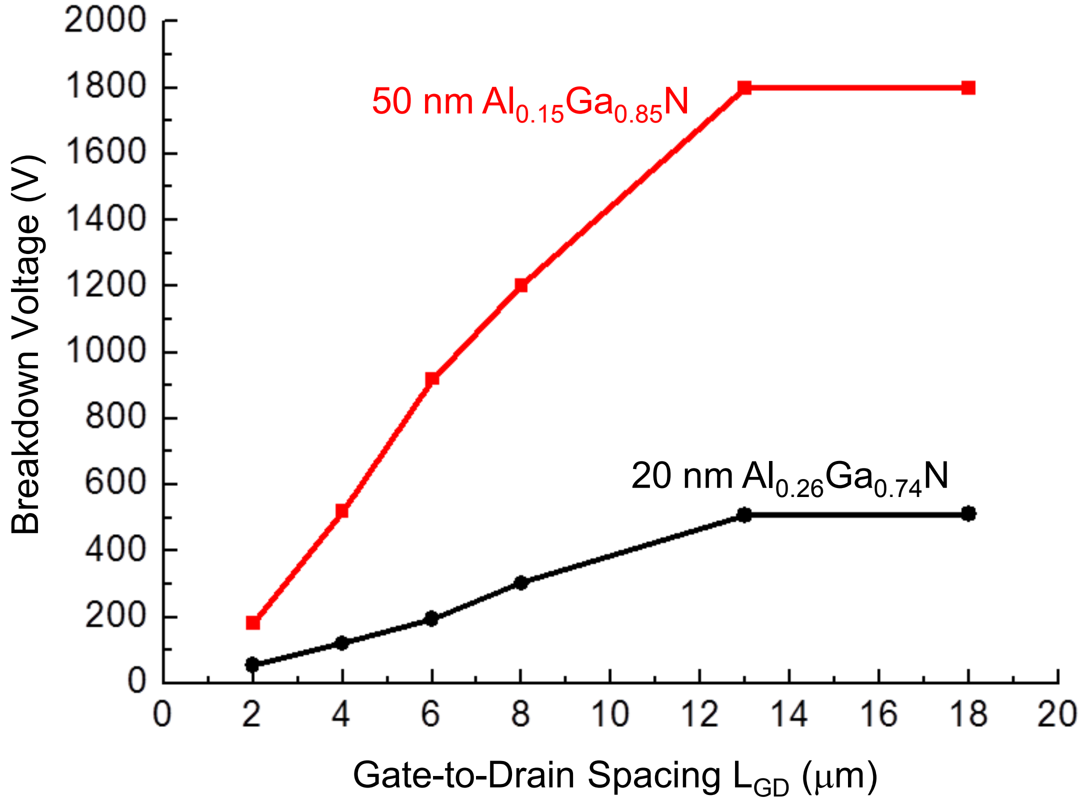
- Designed and fabricated at MIT
- Polarization induces high-μ channel
- Normally-on device
- L_{GD} and Al% control V_{BD}

	Device 1	Device 2	Device 3	Device 4
Maximum V_{BD}	1800 V	1800 V	500 V	500 V
V_{TH}	-3.6 V	-3.6 V	-1.8 V	-1.8 V
Barrier	50 nm $Al_{0.15}Ga_{0.85}N$	50 nm $Al_{0.15}Ga_{0.85}N$	20 nm $Al_{0.26}Ga_{0.74}N$	20 nm $Al_{0.26}Ga_{0.74}N$
Passivation	$Al_2O_3/SiO_2/Al_2O_3$	None	$Al_2O_3/SiO_2/Al_2O_3$	None
C-doped buffer	Yes	Yes	No	No

$L_G = 2\ \mu m$, $L_{GS} = 1.5\ \mu m$, $L_{GD} = 1.5$ to $40\ \mu m$

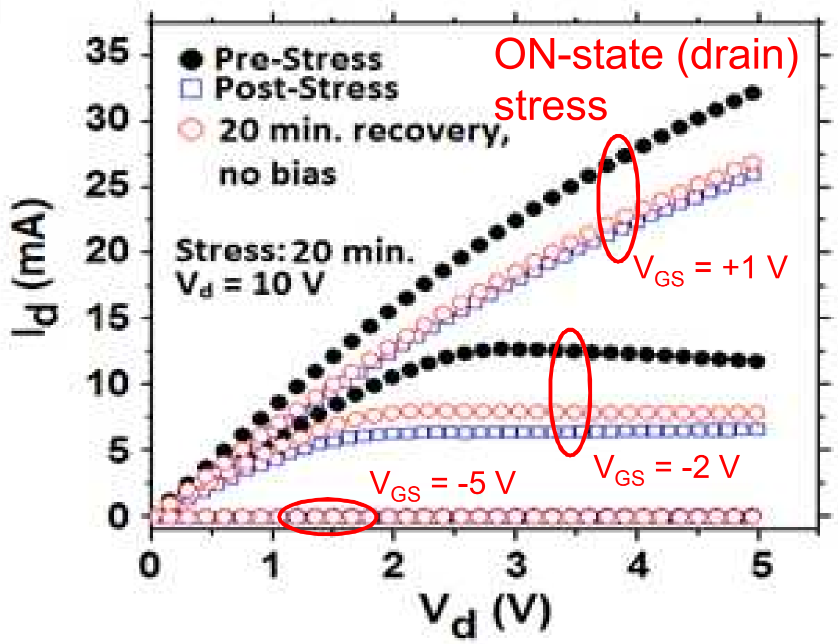
All devices grown on (111) Si by MOCVD

Dependence of Breakdown Voltage on Gate-to-Drain Spacing

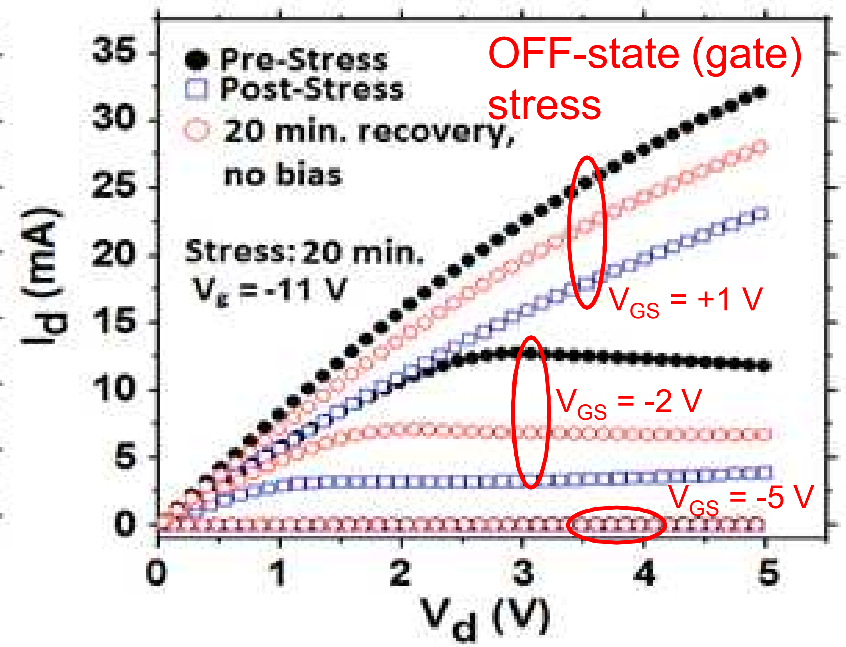


ON-State vs. OFF-State Stress

Passivated $Al_{0.15}Ga_{0.85}N/GaN$ sample



Stress: V_{DS} = 10 V, V_{GS} = 0 V (ON)

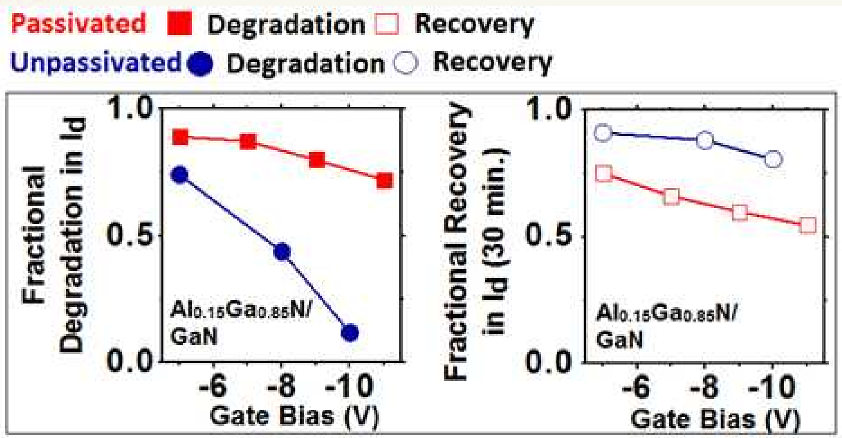


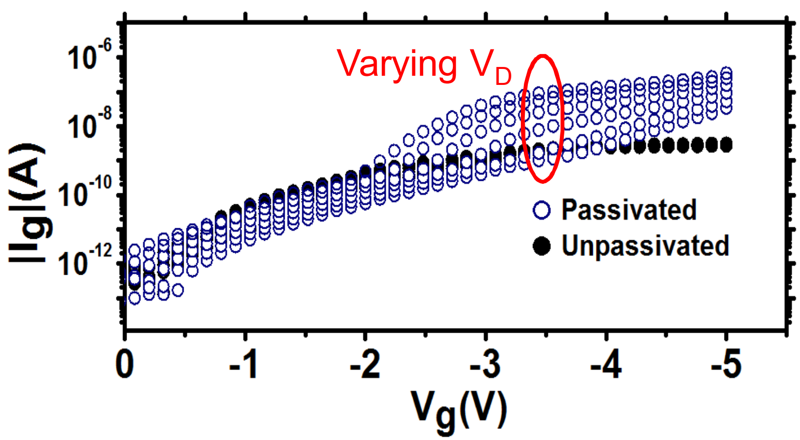
Stress: V_{DS} = 0 V, V_{GS} = -11 V (OFF)

ON-state stress (drain bias) results in much slower recovery than OFF-state stress (gate bias)

S. DasGupta et al., *Transactions on Electron Devices* **59 (8)**, 2115 (2012)

Gate Leakage Current





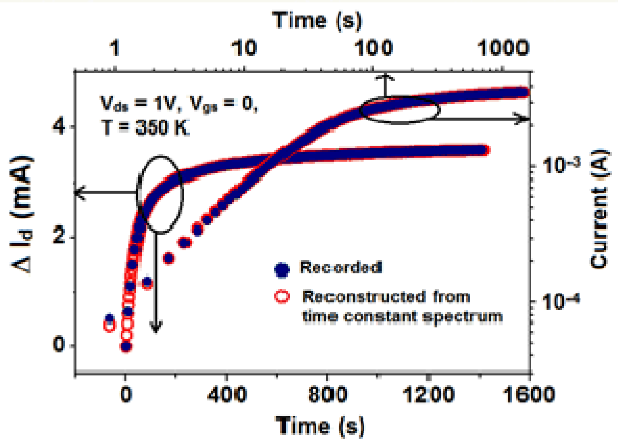
$Al_{0.15}Ga_{0.85}N$ (1800 V_{BD})

- $Al_2O_3/SiO_2/Al_2O_3$ ALD surface passivation greatly improves stability under bias stress, but increases gate leakage current

- Potential problem for high-current devices (large gate width requires very low leakage per unit length)

S. DasGupta et al., *Transactions on Electron Devices* **59 (8)**, 2115 (2012)

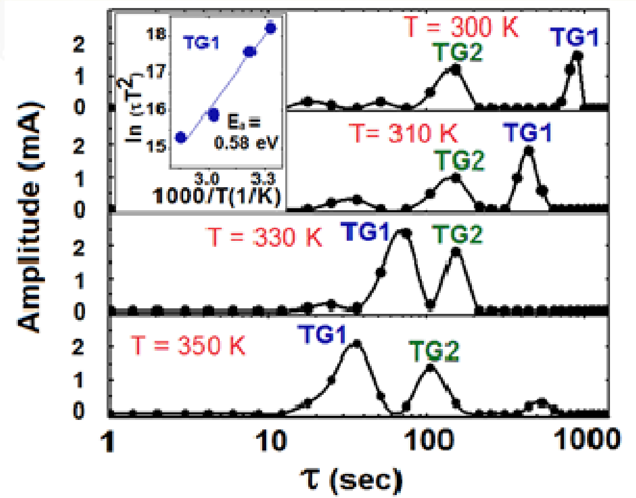
Recovery Current Transient Analysis Following Gate Stress



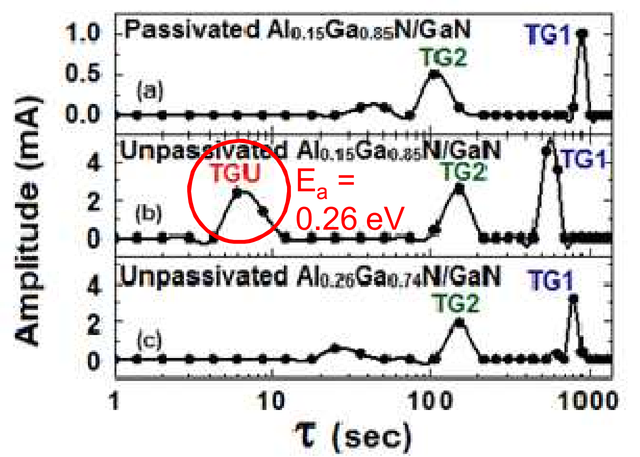
Fitting of recovery transient amplitudes A_i with fixed τ_i:

$$\Delta I_d = \sum_i A_i \left[1 - exp\left(-\frac{t}{\tau_i}\right)\right]$$

Peaks in time constant spectra are indicative of different traps in different samples



Passivated $Al_{0.26}Ga_{0.74}N/GaN$ temperature dependence



Comparison of other samples

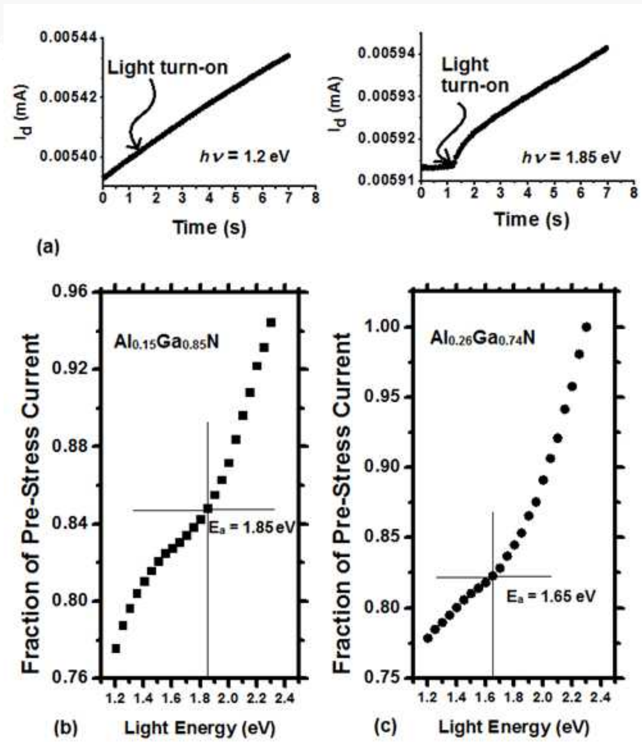
S. DasGupta et al., *Transactions on Electron Devices* **59 (8)**, 2115 (2012)

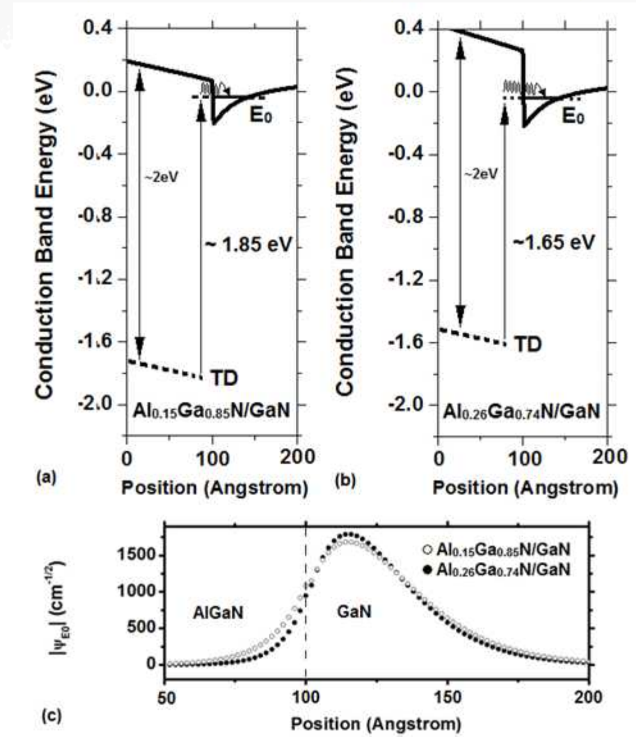
Optical Recovery of Drain-Stress-Induced Trap

15% Al

7 s exposure at each λ

V_{DS} = 1 V
V_{GS} = 0 V

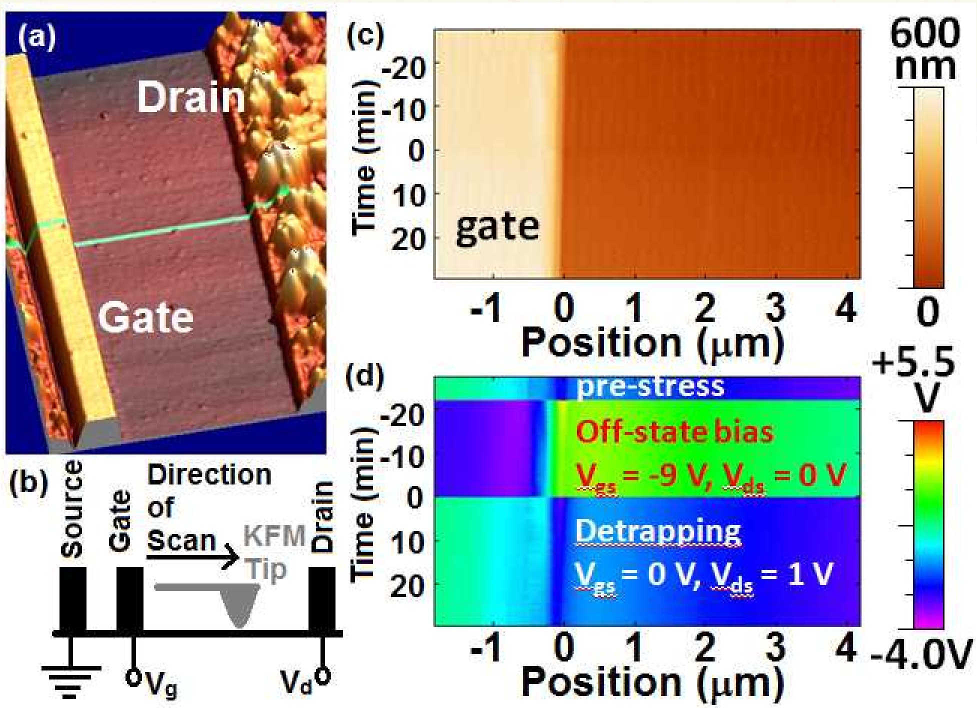




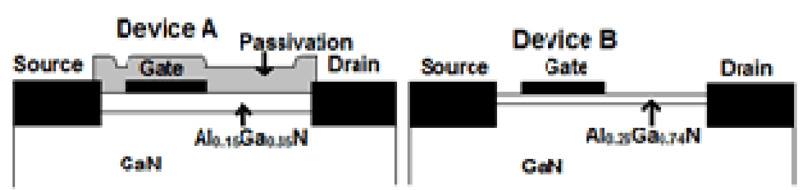
Inflection point (d^2I/dE^2) depends on barrier composition; consistent with transition from a deep level E_C – 2.0 eV in the AlGaN to the 2DEG

S. DasGupta et al., *Transactions on Electron Devices* **59 (8)**, 2115 (2012)

Kelvin Force Microscopy Methodology

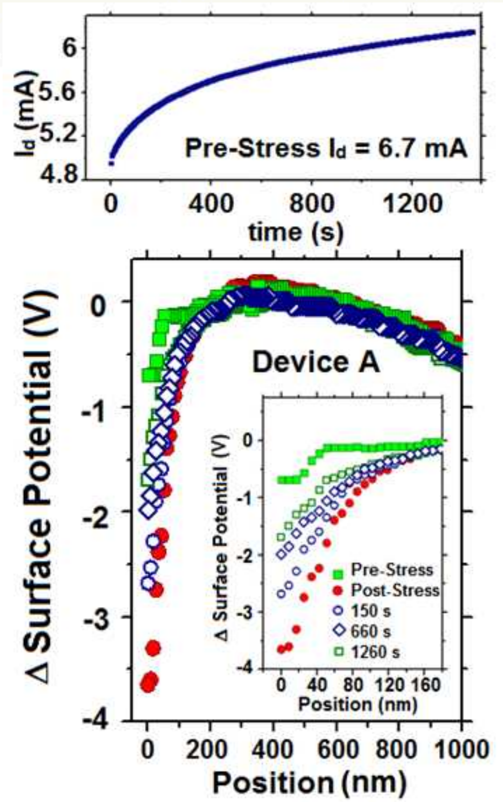


Device type	AlGaN Barrier	GaN Buffer	Passivation
A (1)	50 nm $Al_{0.15}Ga_{0.85}N$	Carbon doped	ALD deposited $Al_2O_3/SiO_2/Al_2O_3$
B (4)	20 nm $Al_{0.26}Ga_{0.74}N$	Undoped	None



Device A: Expect *bulk* trapping
Device B: Expect *surface* trapping

Correlated Surface Potential and Drain Current Following Gate Stress



Device type	AlGaN Barrier	GaN Buffer	Passivation
A (1)	50 nm $Al_{0.15}Ga_{0.85}N$	Carbon doped	ALD deposited $Al_2O_3/SiO_2/Al_2O_3$
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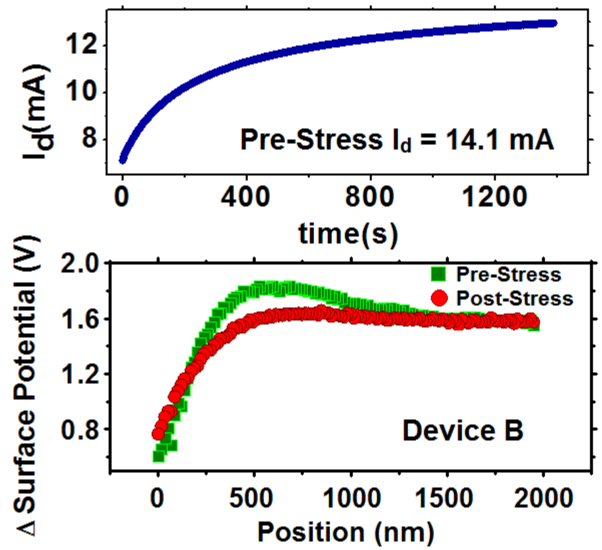


Device A: *Large* change in surface potential near the gate edge

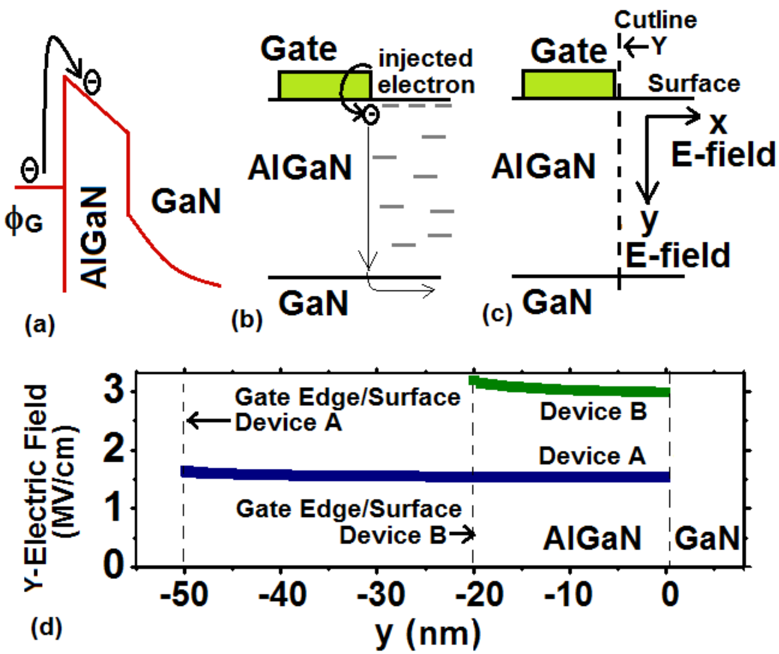
Device B: *Negligible* change in surface potential throughout the drain extension

Results inconsistent with expectations based on buffer doping and surface passivation

S. DasGupta et al., *Applied Physics Letters* **101**, 243506 (2012)

Proposed Explanation: Barrier Thickness Dependence

Device type	AlGaN Barrier	GaN Buffer	Passivation
A (1)	50 nm $Al_{0.15}Ga_{0.85}N$	Carbon doped	ALD deposited $Al_2O_3/SiO_2/Al_2O_3$
B (4)	20 nm $Al_{0.26}Ga_{0.74}N$	Undoped	None

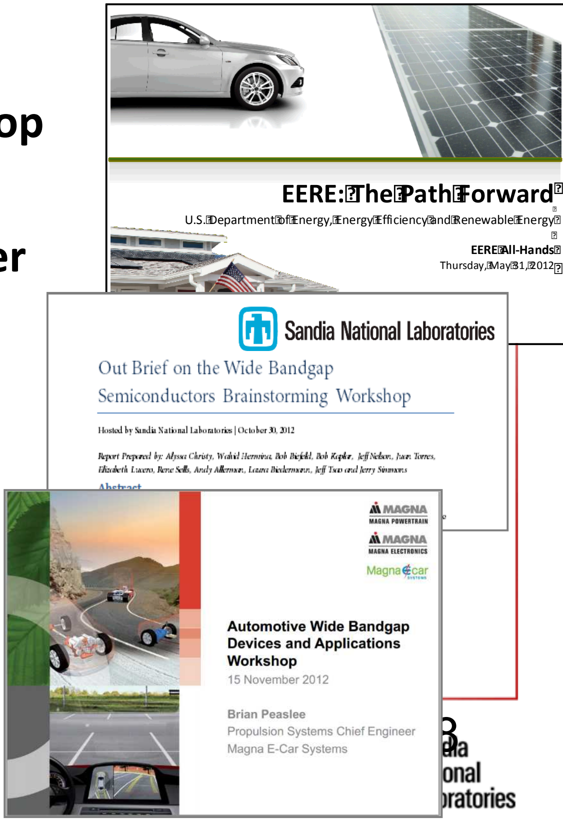


- Under gate stress, injected electrons experience a higher vertical electric field for a thin barrier (device B) than for a thick barrier (device A)
- Thus, an electron in a thin-barrier HEMT (device B) is less likely to be trapped in the barrier and is more likely to reach the channel than an electron in a thick-barrier HEMT (device A)
- Explains AlGaN trapping in thick-barrier HEMT (device A) and GaN/channel trapping in thin-barrier HEMT (device B)
- *Indicates that device design and the internal electric field distribution are at least as important as the trap distribution in determining HEMT reliability*

S. DasGupta et al., *Applied Physics Letters* **101**, 243506 (2012)

Increasing DOE Interest in WBGs

- **2010 ARPA-E ADEPT Program:** "Agile Delivery of Electric Power Technology," $34.5M
- **Feb 1, 2012:** Chu's Materials for Energy Applications workshop, Berkeley – *WBGs one of four major topics in Chu's talk*
- **May 31, 2012:** EERE—New undersecretary David Danielson announces WBG's as one of his four major initiatives
- **June 26, 2012: SNL Workshop on Power Electronics**
- **July 25, 2012: WBG Semiconductors for Clean Energy Workshop** (Dave Danielson, DOE/AMO Invitation-only)
- **Sept. 11 and Oct. 23, 2012: Robust WBG Semiconductor Power Electronics Workshops** (ANL and the University of Maryland)
- **October 30, 2012: SNL WBG Semiconductors Brainstorming Workshop** - *Outlined a Center concept for review from participants*
- **Nov. 15-16, 2012: Automotive Wide Bandgap Devices and Applications** (Oak Ridge National Laboratory)
  - *Wide Bandgap devices for the next generation of electric drive systems*



The Need for a National WBG Center

A National Center for Innovation in Wide-Bandgap Semiconductors would

- Spur innovation and enhance competitiveness of U.S. industry
- Improve energy efficiency and incorporation of renewable energy sources
- Enable intelligent, resilient energy grids

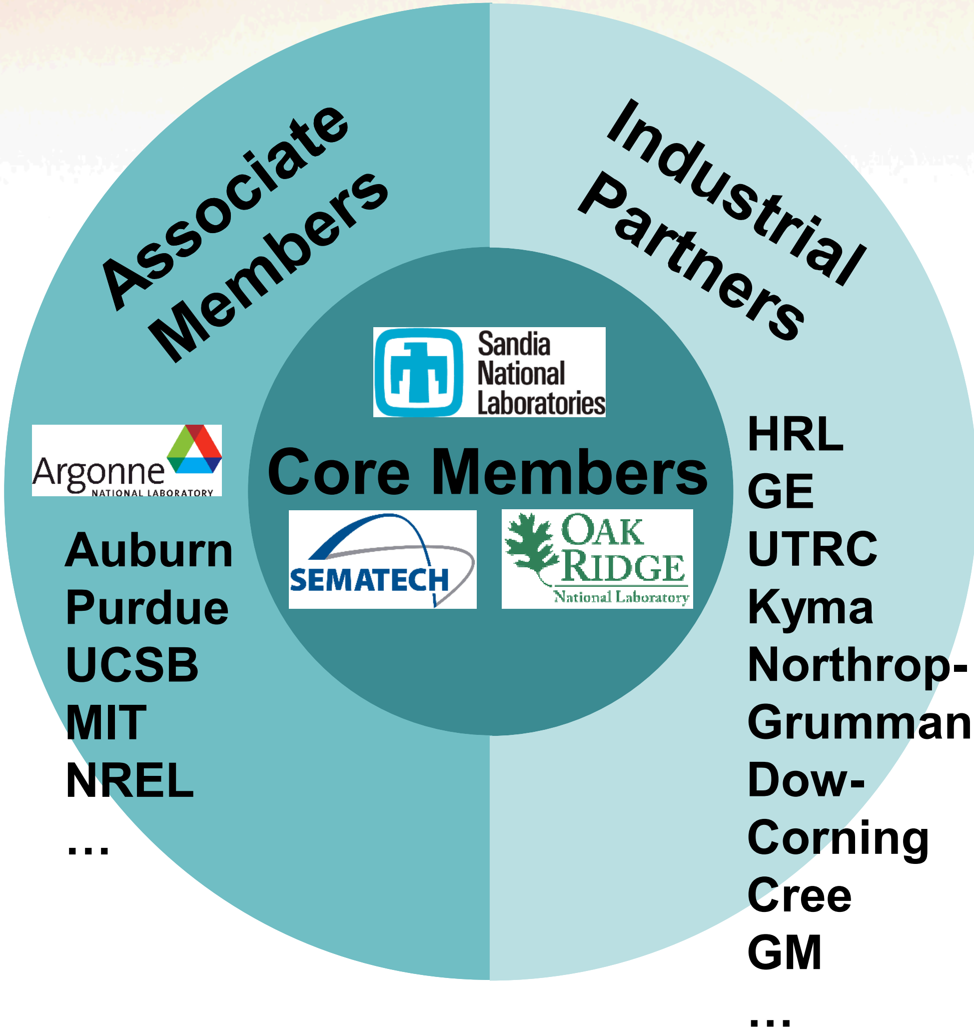
This center would build on Sandia's established excellence in

- III-N WBGs for solid-state lighting
- Fabrication, testing, and failure analysis at MESA and CINT
- PV reliability at DETL and microgrid GC LDRD
- Existing power electronics work (energy storage program)

Sandia National Laboratories SEMATECH OAK RIDGE National Laboratory

Sandia National Laboratories

Proposed Center Structure



Core Members (3):
Collectively possess a suite of capabilities unique in its degree of vertical integration and its ability to support collaboration at any level of the technology innovation chain.

Associate Members (~5-10):
Non-profits who will contribute their complimentary capabilities to the Center.

Industrial Partners (~15-20):

- **Industrial Collaborators** drive the Center's response to industrial needs
- **Industrial Users** utilize Center resources to enhance US industrial competitiveness

National Center Technical Scope

Summary

- WBG power devices promise to increase efficiency and reduce system complexity, but materials and reliability issues have hampered their adoption
- Sandia possesses a full range of WBG capabilities spanning from fundamental materials science to grid-level power systems
- WBG power device work to date has focused on III-N materials for solid-state lighting, as well as both SiC and GaN power devices
- An opportunity exists to establish a DOE-sponsored "national center" of excellence to study WBG materials and devices for energy efficiency and resiliency and we would like Auburn to be part of it

Sandia National Laboratories